Indirect Detection of Dark Matter

Simona Murgia, SLAC-KIPAC

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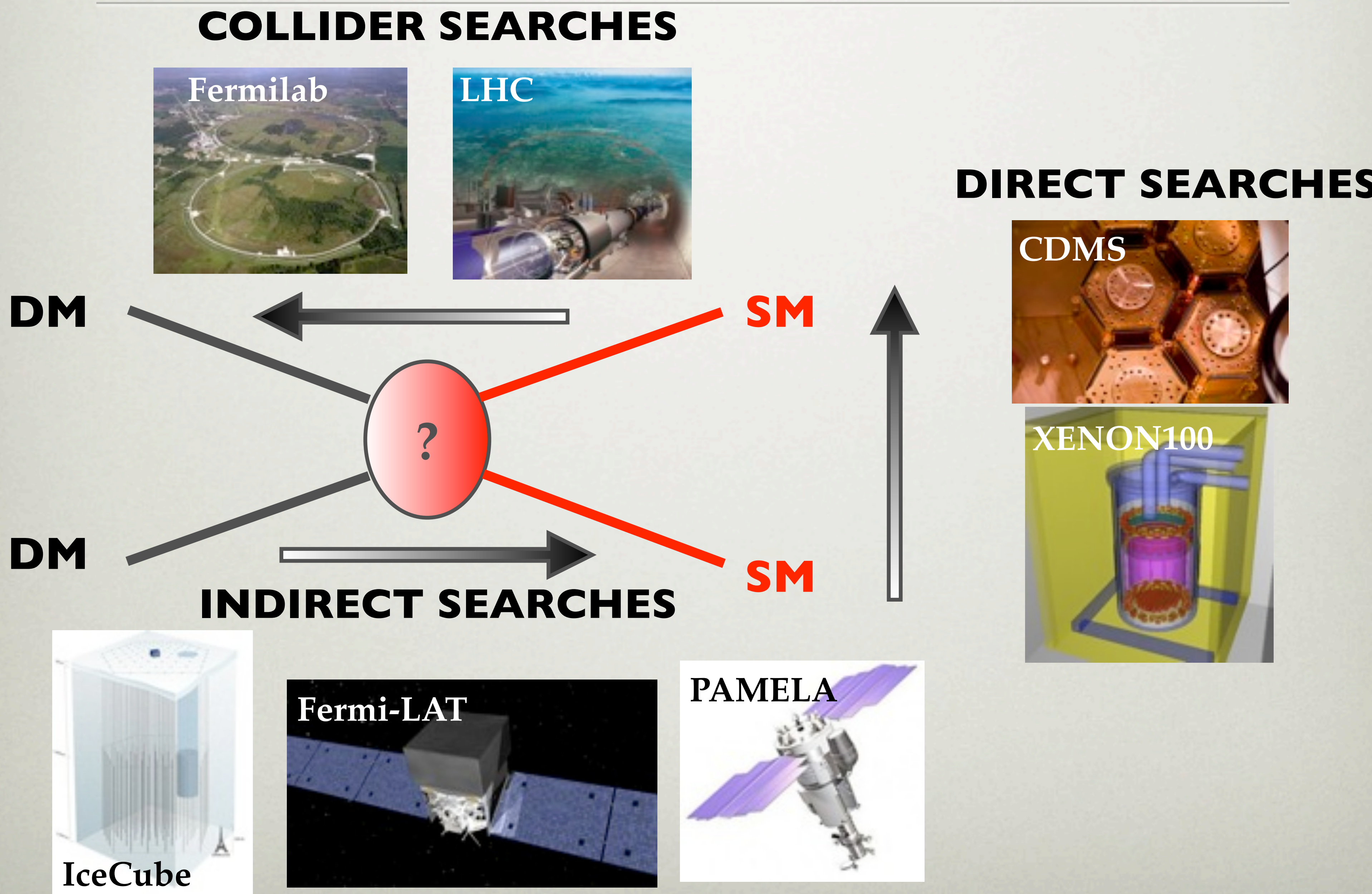
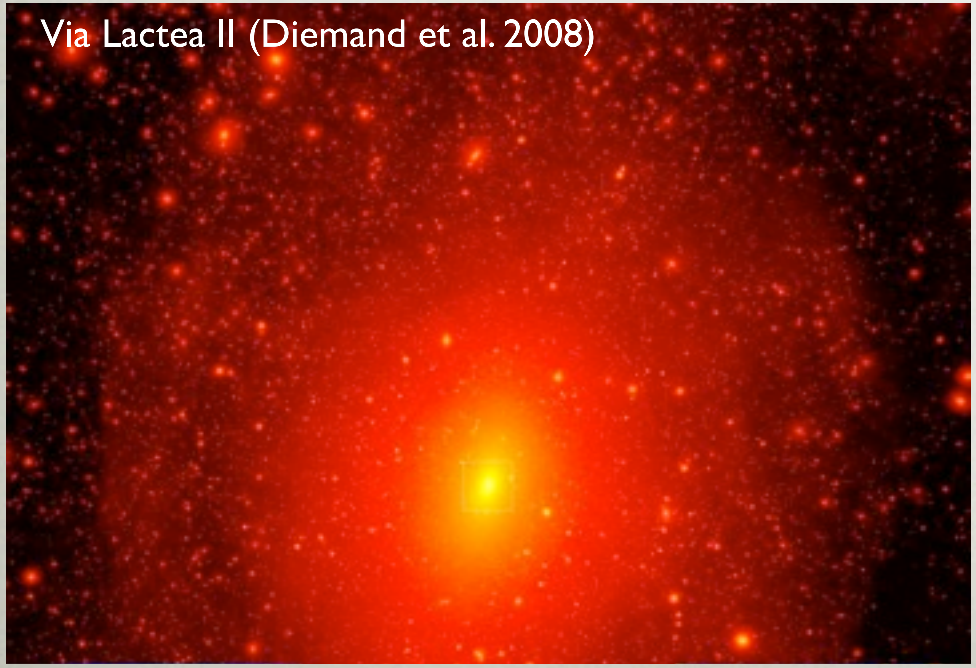
31 August 2011

Dark Matter Searches



Indirect Searches

- Search cosmic rays for the byproducts of dark matter annihilation/decay
- Very rich search strategy, multi-messenger and multi-wavelength
  - neutral: photons, neutrinos
  - charged: electrons, antimatter (positrons, antiprotons, antideuterons, ...)



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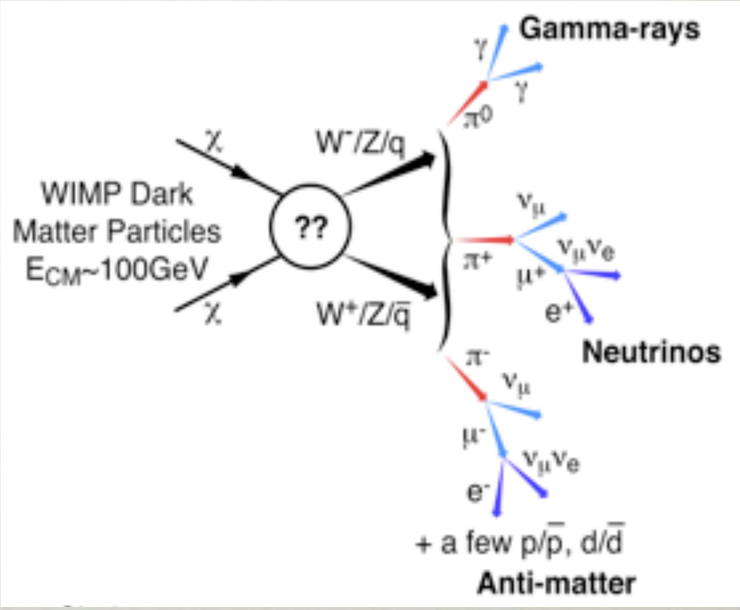

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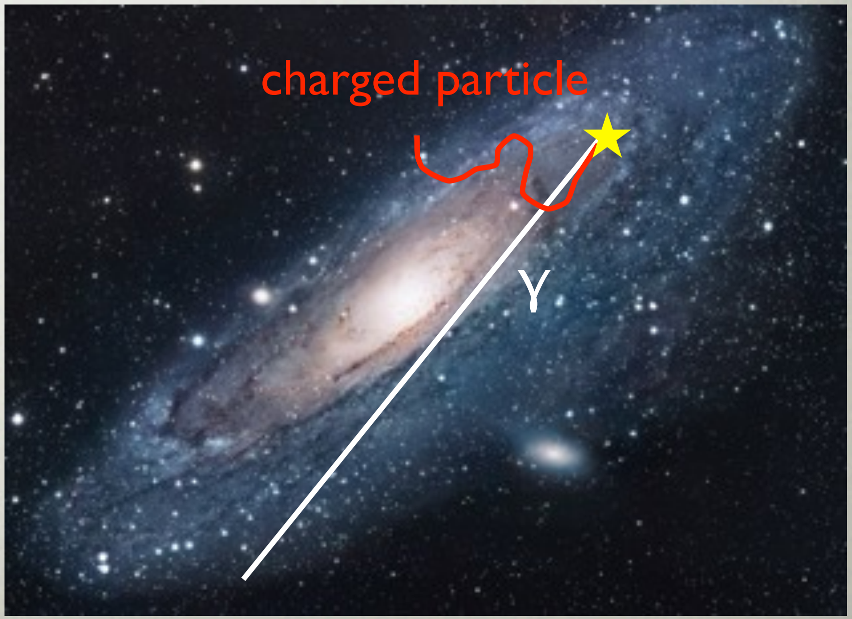
- Very rich search strategy, multi-messenger and multi-wavelength
  - neutral: photons, neutrinos
  - charged: electrons, antimatter (positrons, antiprotons, antideuteron, ...)
- Generally, neutral particles are more promising probes
  - No loss of energy, directionality for neutrinos, gamma-rays ⇒ point back to source and preserve spectral information (on galactic scales)
  - Charged particles lose energy, directionality on their way to us ⇒ important information on their origin is lost



WIMP Signal

- E.g. photons from DM annihilation:

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) \quad = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$

$$\times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}$$

DM distribution

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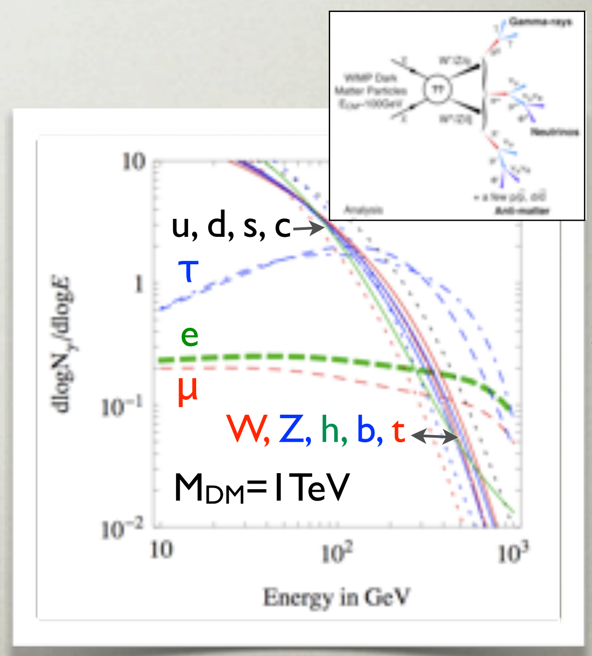

Cirelli et al, arXiv:0809.2409

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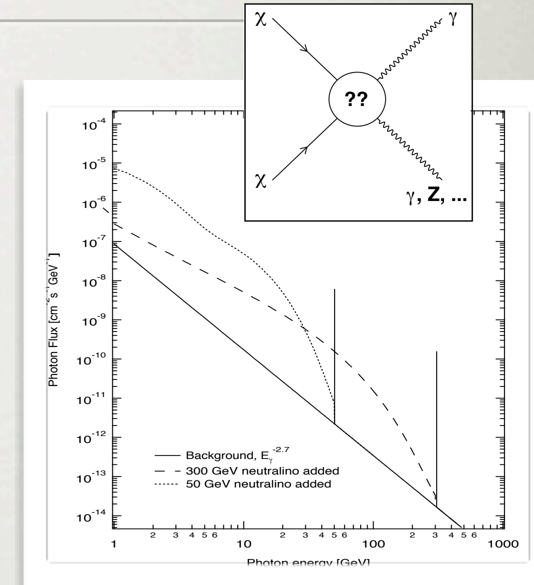
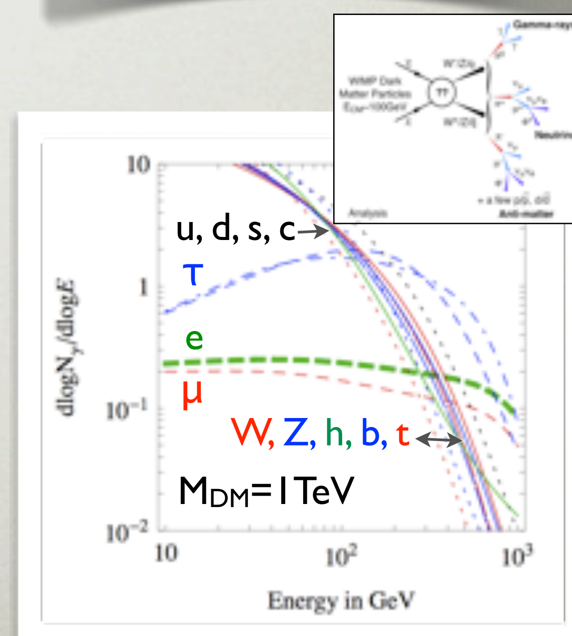


Bergstrom, Ullio, Buckley



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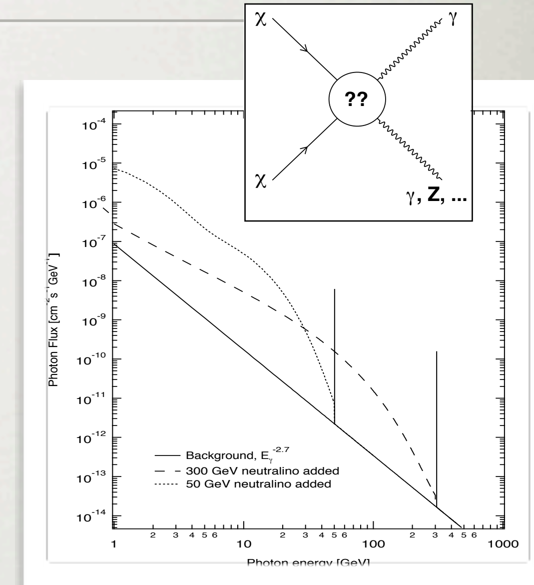

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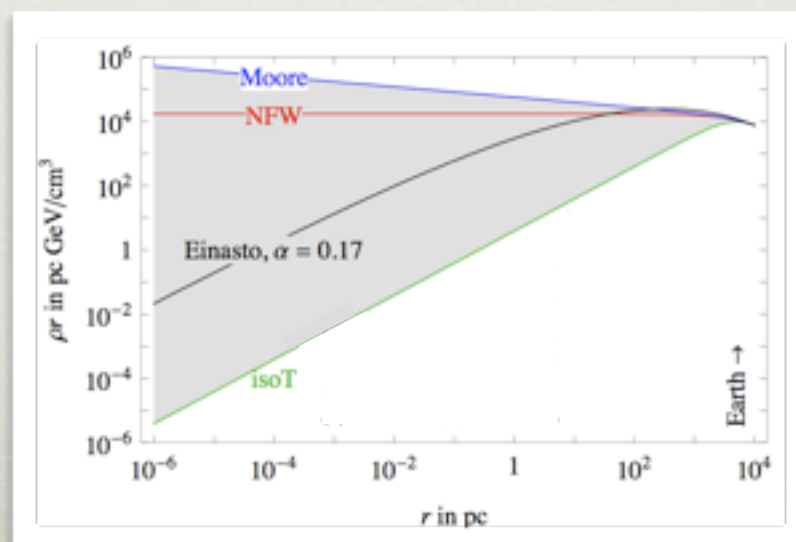

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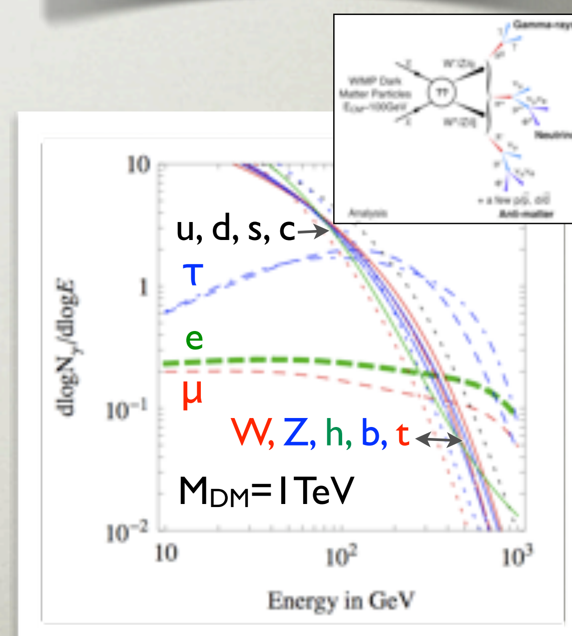

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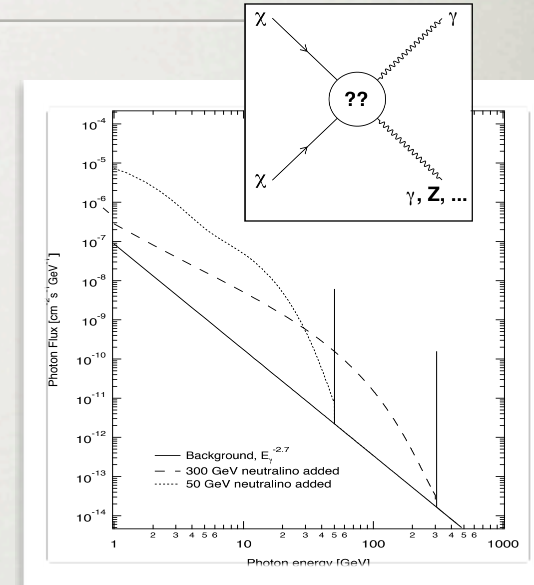
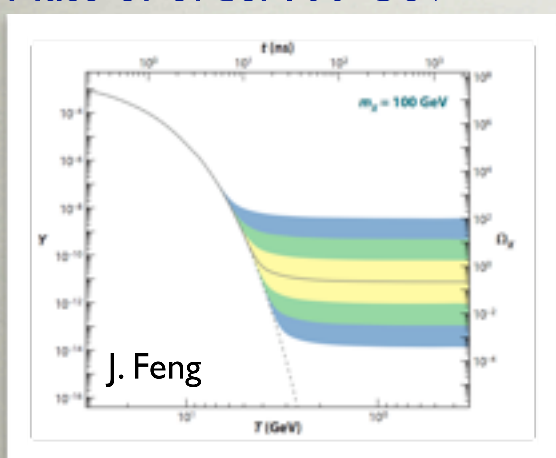
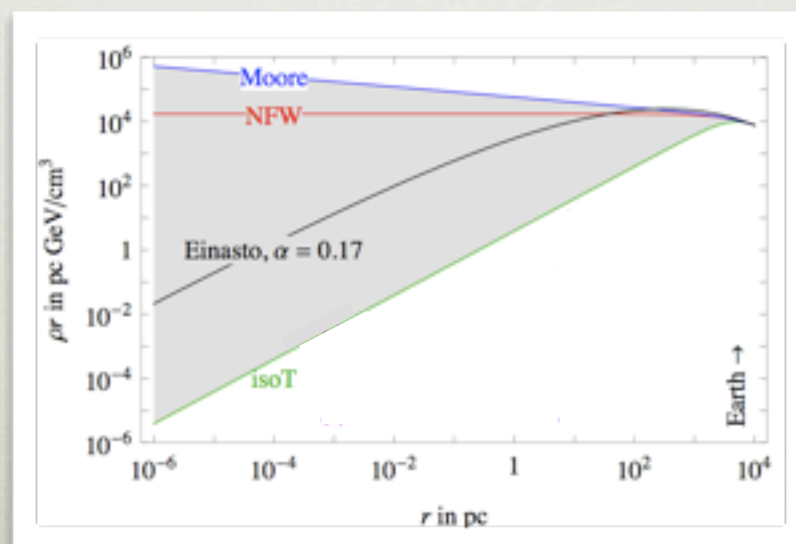


Bergstrom, Ullio, Buckley

Thermal WIMP
$<\sigma v>$ of order 3×10^{-26} cm^3/s
Mass of order 100 GeV





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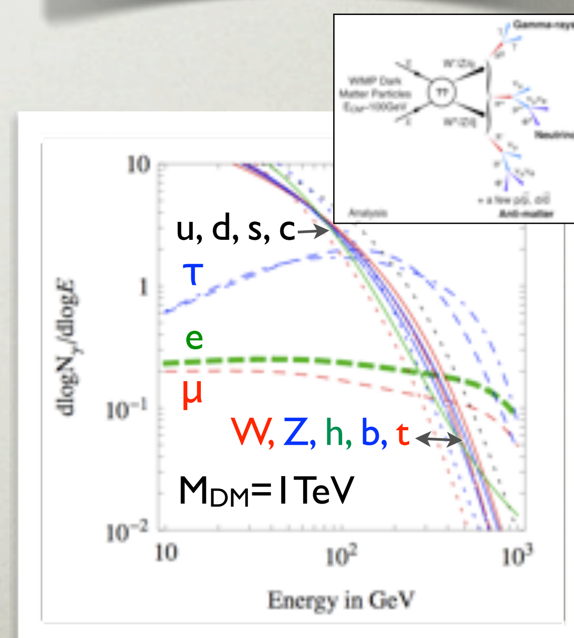

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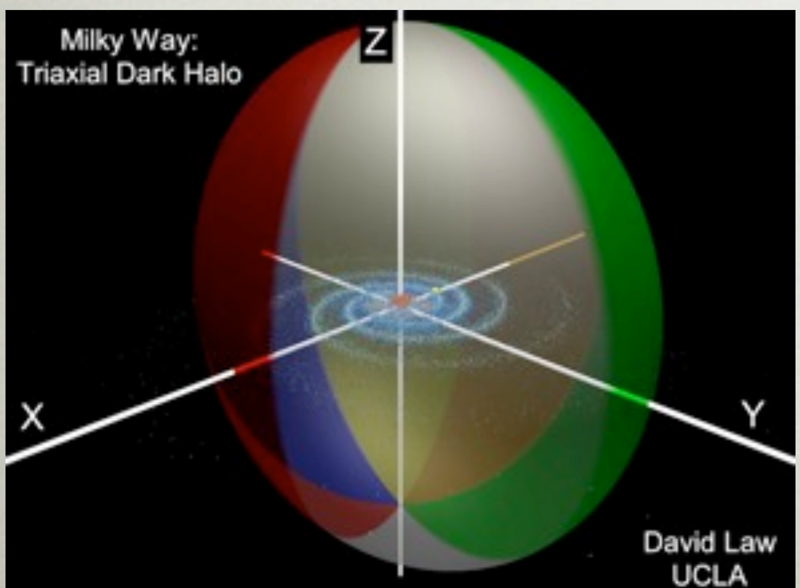
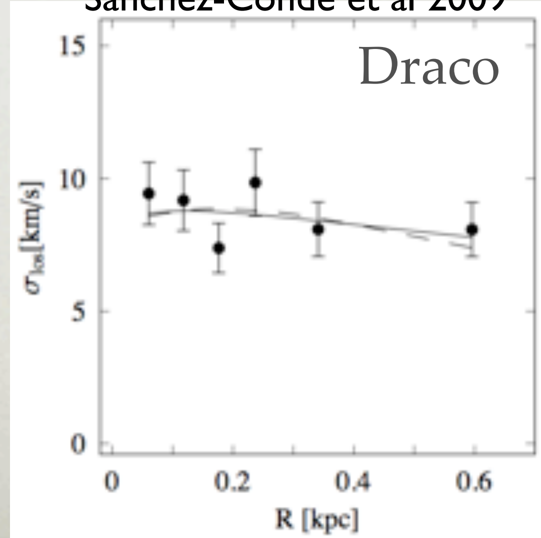
Dark Matter Distribution

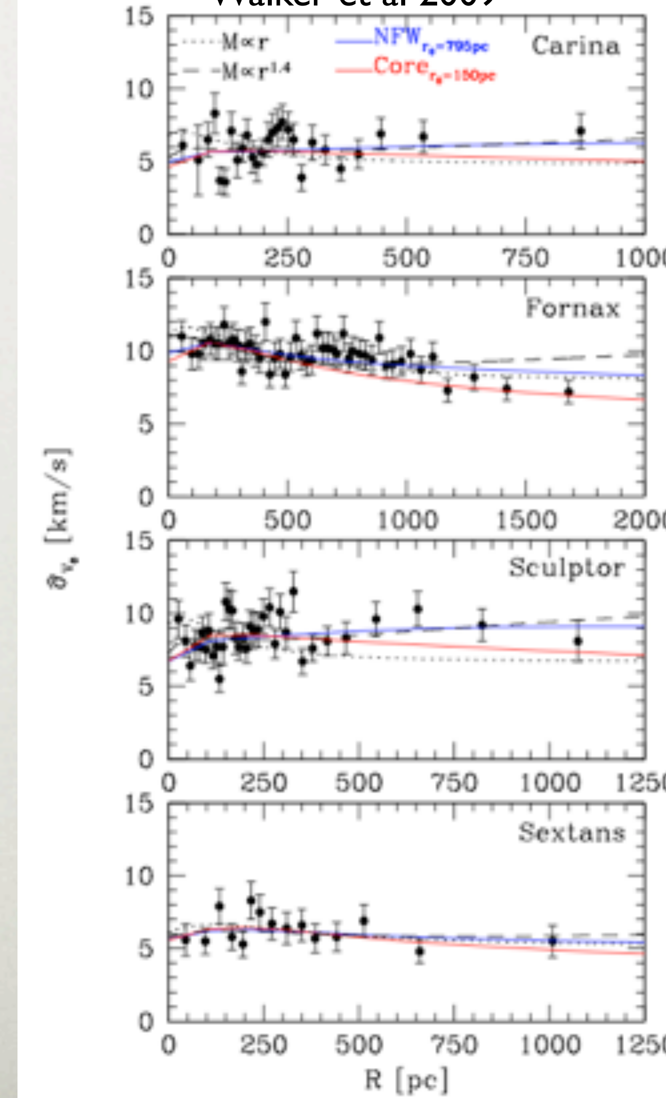
- We generally heavily rely on simulations of the dark matter distribution to make predictions for DM searches...
- ... but much is still unknown on how DM is distributed, e.g.:
  - cuspiness of the profile
  - halo shape (spherical, prolate, oblate, triaxial, dark disk, ...)
  - substructure



Sanchez-Conde et al 2009

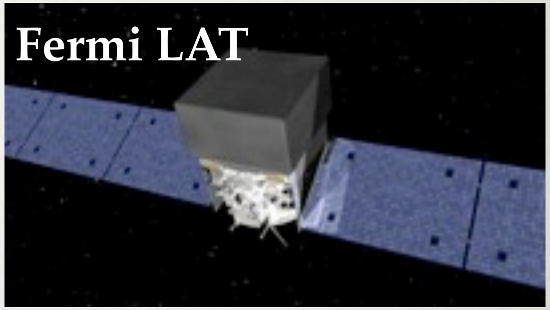


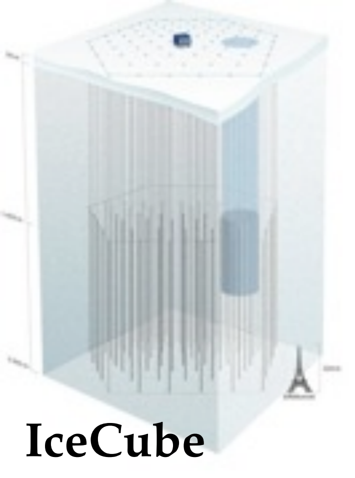
Walker et al 2009



EXPERIMENTS

- **Gamma rays**
  - Fermi LAT
  - HESS
  - MAGIC
  - VERITAS
- **Cosmic Rays**
  - PAMELA
  - Fermi LAT
- **Neutrinos**
  - IceCube



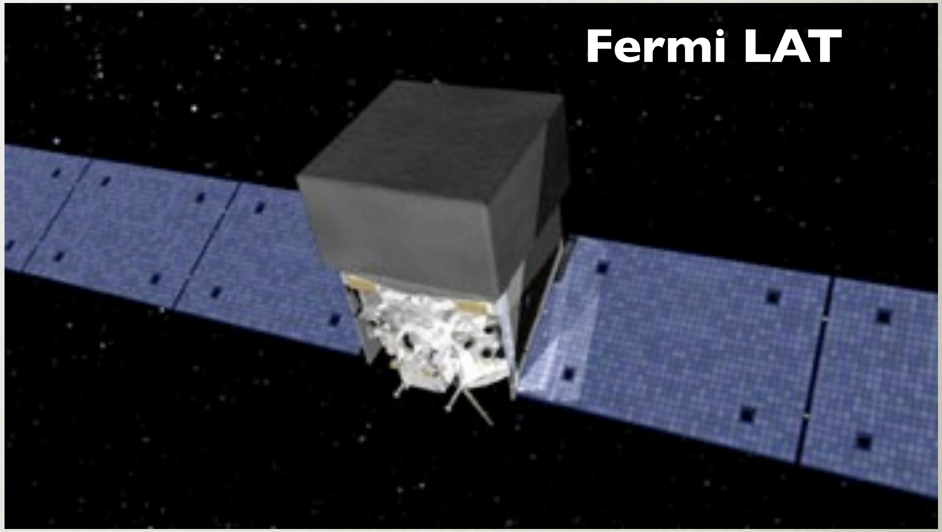


Gamma rays

ON THE GROUND

IN SPACE

Atmospheric Cherenkov Telescopes (ACTs)

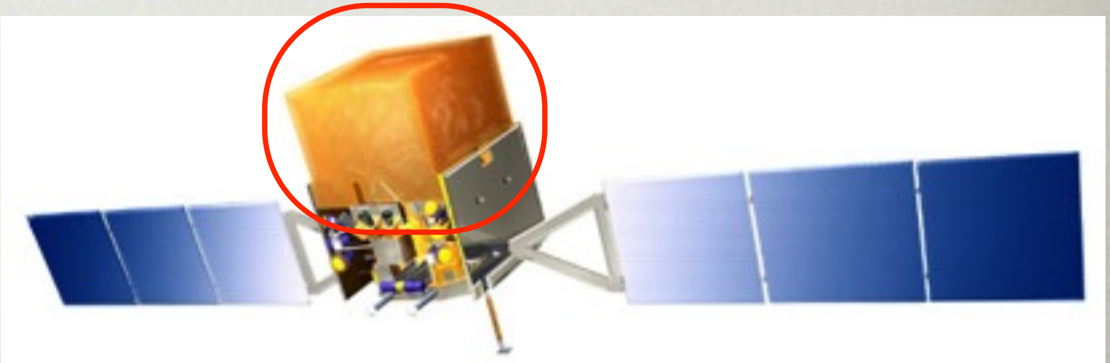


The Fermi LAT

- Observe the gamma-ray sky in the 20 MeV to >300 GeV energy range with unprecedented sensitivity

- Orbit: 565 km, 25.6° inclination, circular. The LAT observes the entire sky every ~3 hrs (2 orbits)

Large Area Telescope (LAT)



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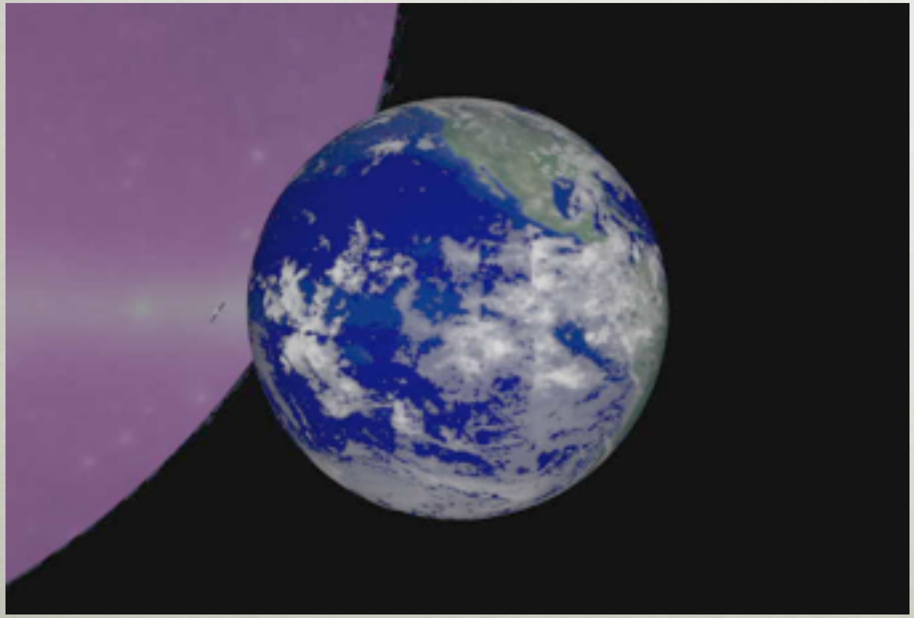
Launch (June 2008)



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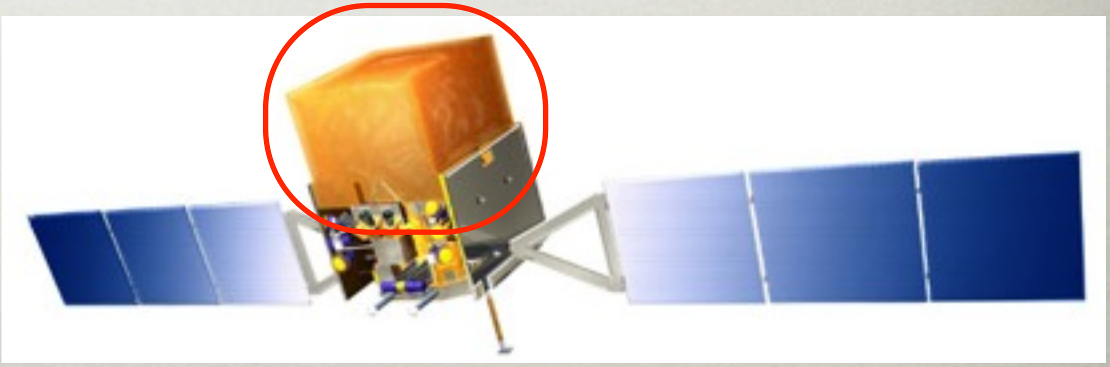
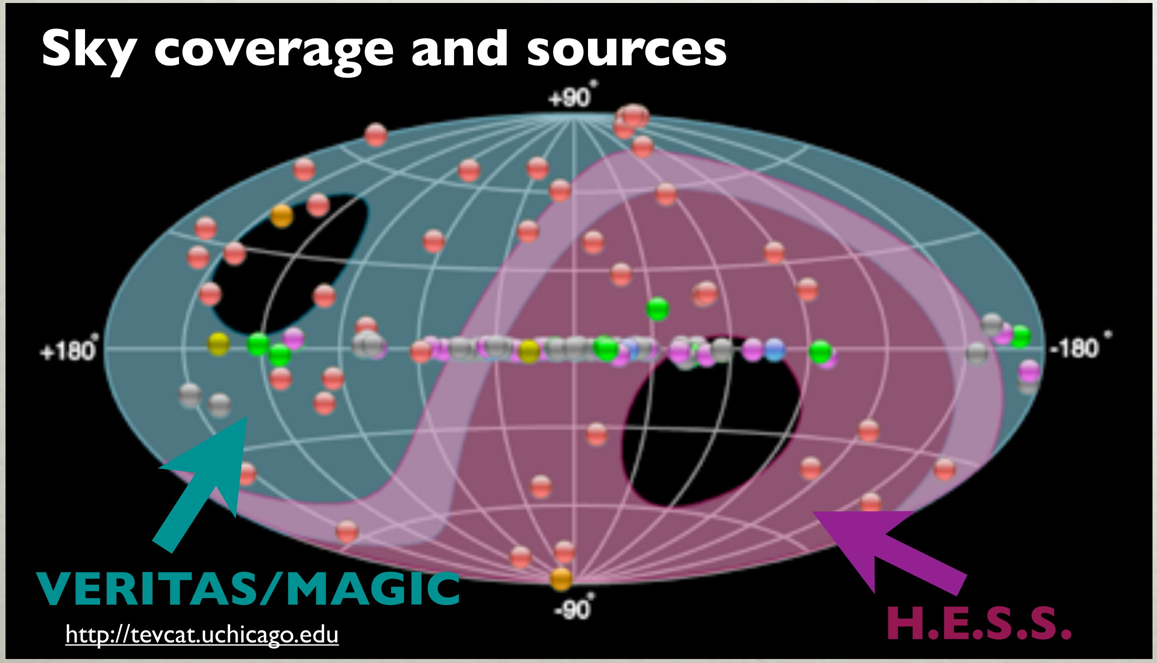
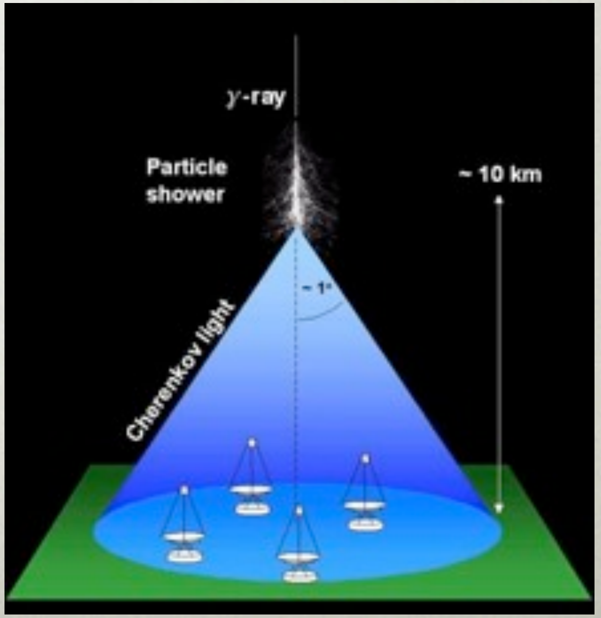


Very High Energy Gamma rays

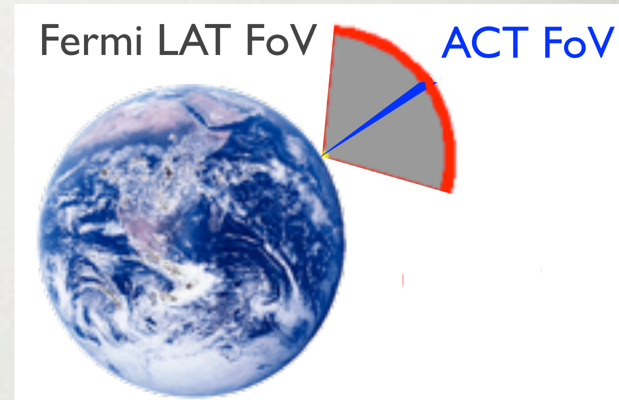
Imaging Atmospheric Cherenkov Telescopes (IACTs)

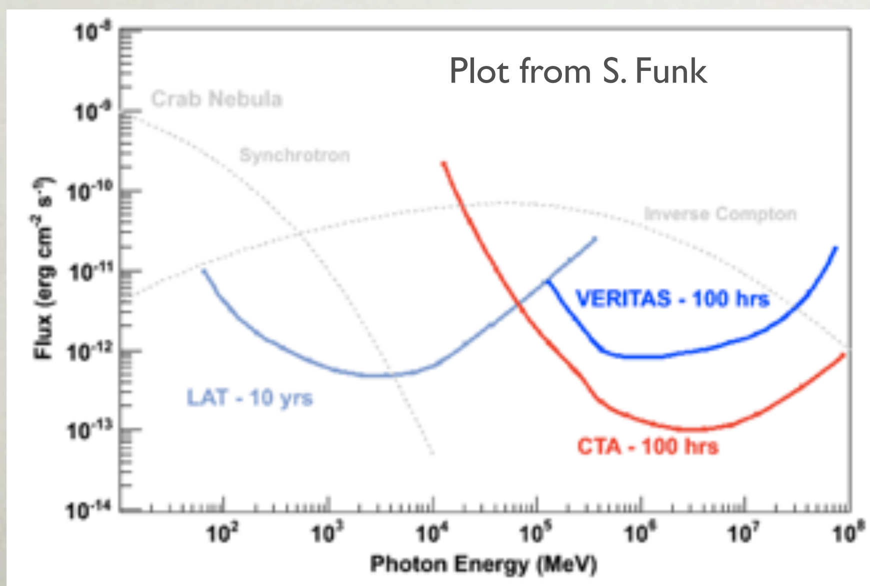


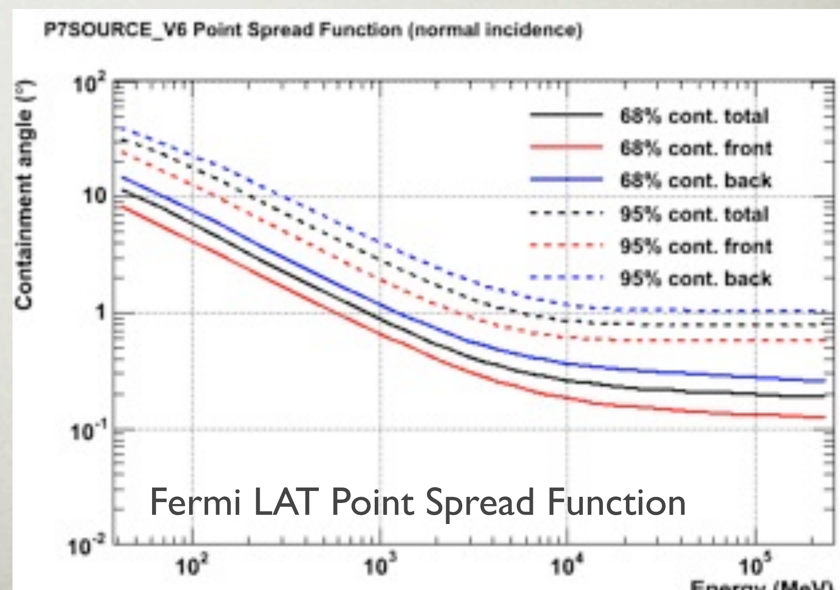


Ground vs Space Gamma-ray Experiments

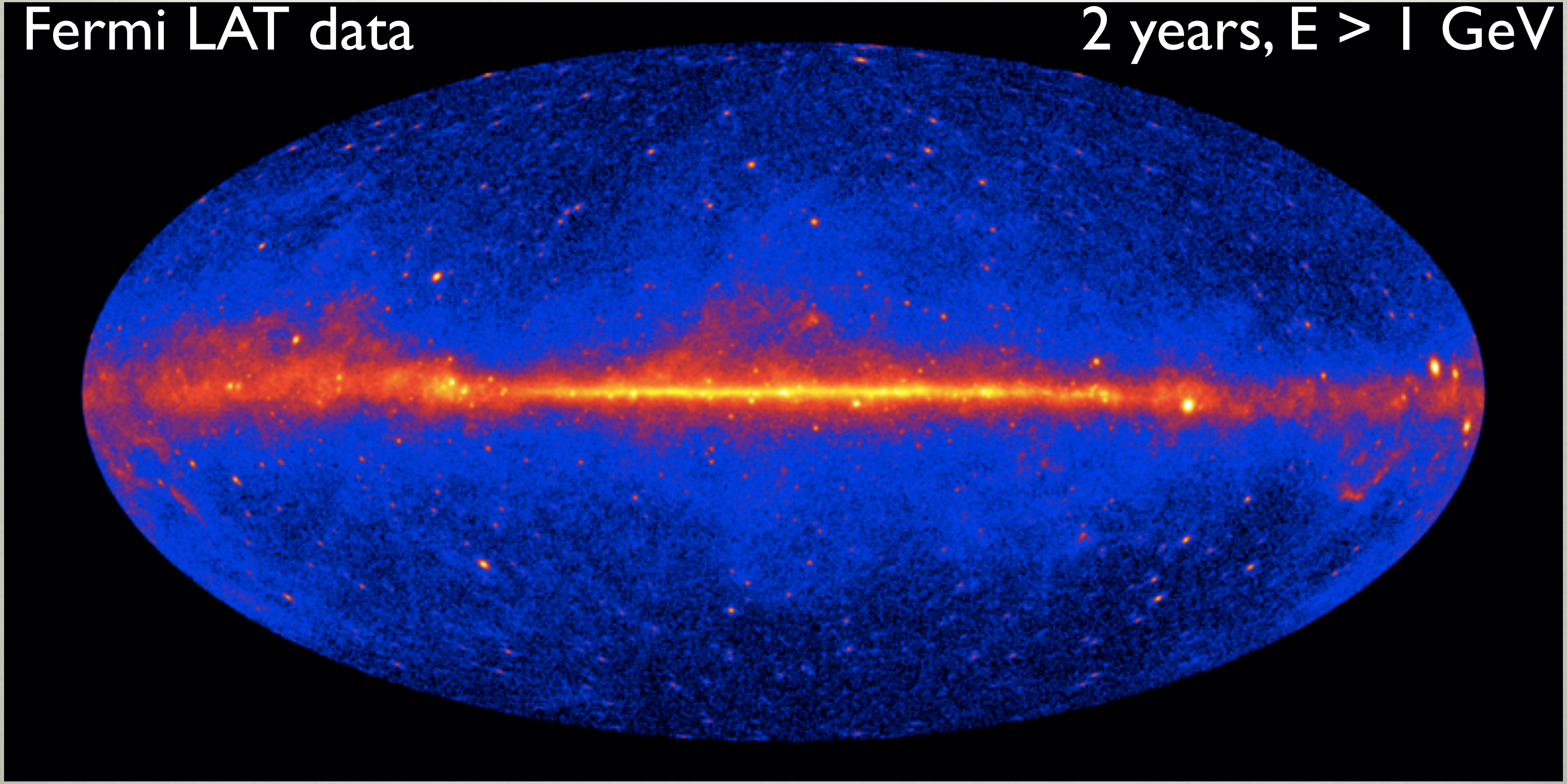
- Lower energy thresholds accessible in space, and up to ~100 TeV energies with experiments on the ground. Overlap in the ~100 GeV region
- Larger field of view, great duty cycle, and all sky coverage in space
- Single photon angular resolution: ~1° at 1 GeV (Fermi LAT), ~0.1° at 100 GeV (ACTs, Fermi LAT), ~0.05° at 1 TeV (ACTs)
- Energy resolution: ~ 8% at 10 GeV (Fermi LAT), ~15% at 1 TeV (ACTs)
- Large collecting area on the ground (high sensitivity)



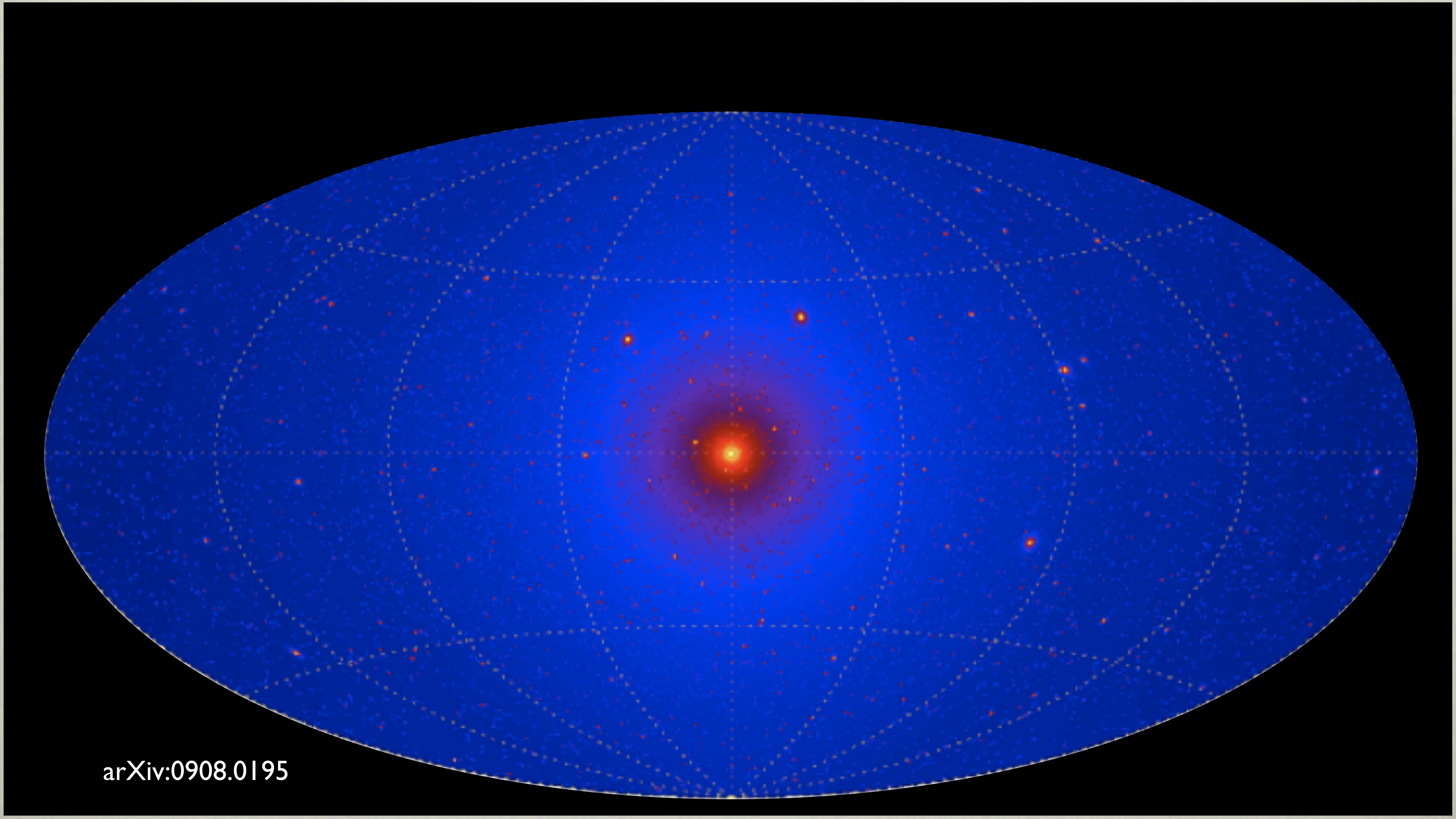




The Fermi Sky



Gamma rays from DM Annihilation



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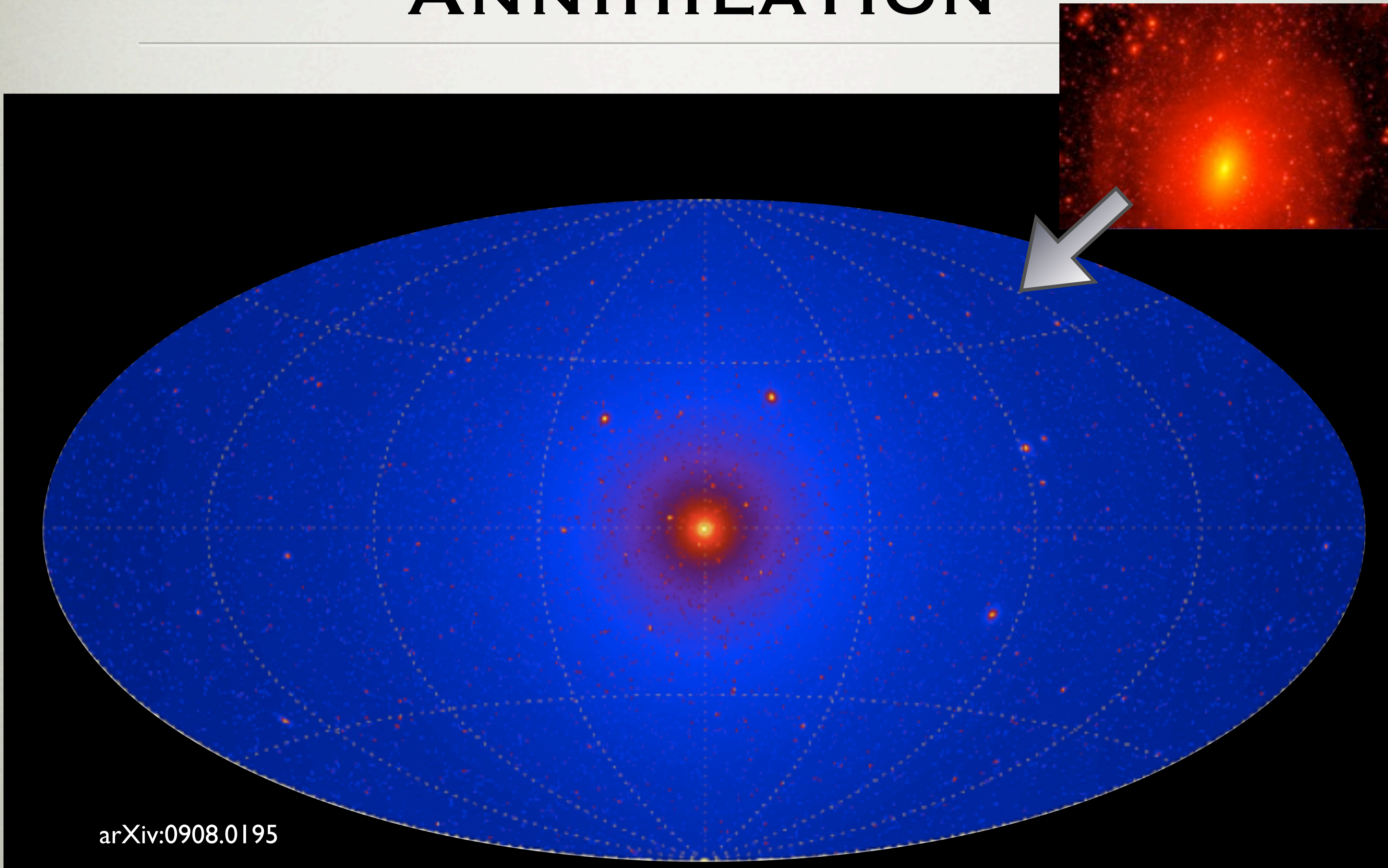
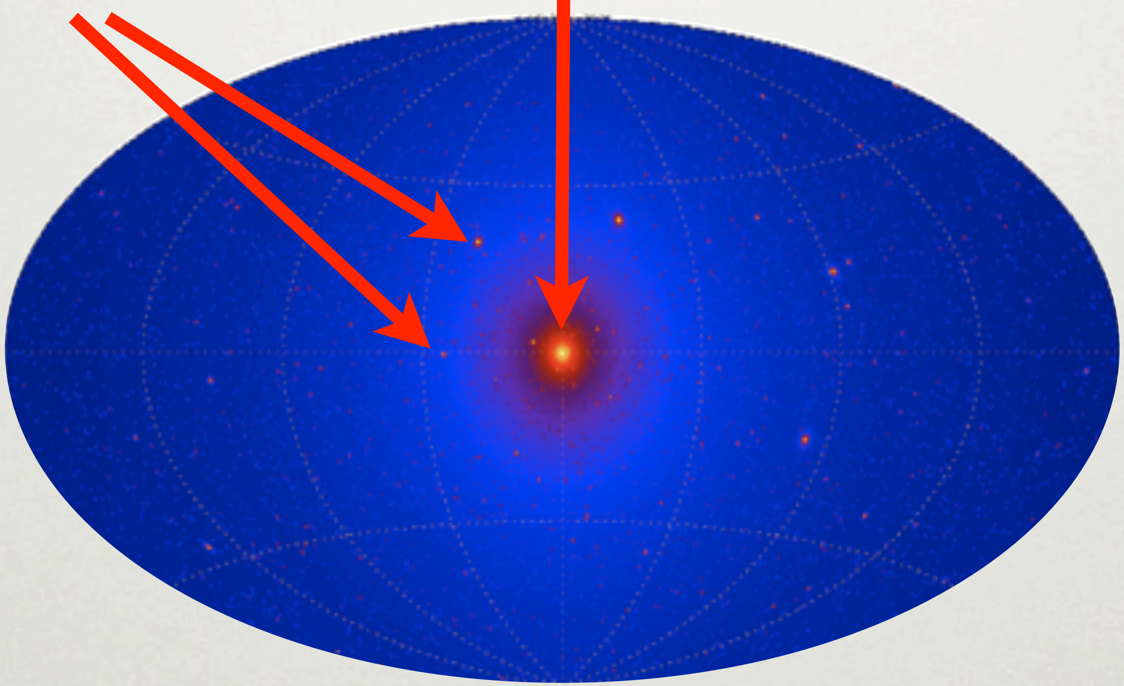


Search Strategies

Galactic center:
Good statistics but source confusion/diffuse background

Satellites:
Low background and good source ID, but low statistics

Milky Way halo:
Large statistics but diffuse background



+Electrons!

Anisotropies

Spectral lines:
No astrophysical uncertainties, good source ID, but low statistics

Galaxy clusters:
Low background but low statistics

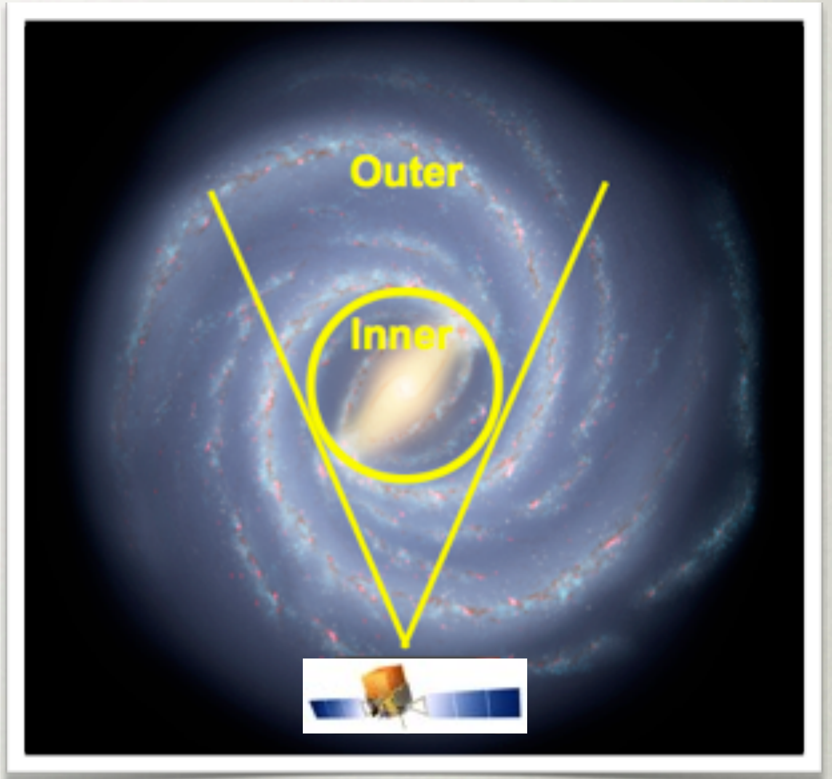
Extragalactic:
Large statistics, but astrophysics, Galactic diffuse background

Galactic Center Region

☺ Steep DM profiles ⇒ Expect large DM annihilation/decay signal from the GC!

☹ Good understanding of the astrophysical background is crucial to extract a potential DM signal from this complex region of the sky:

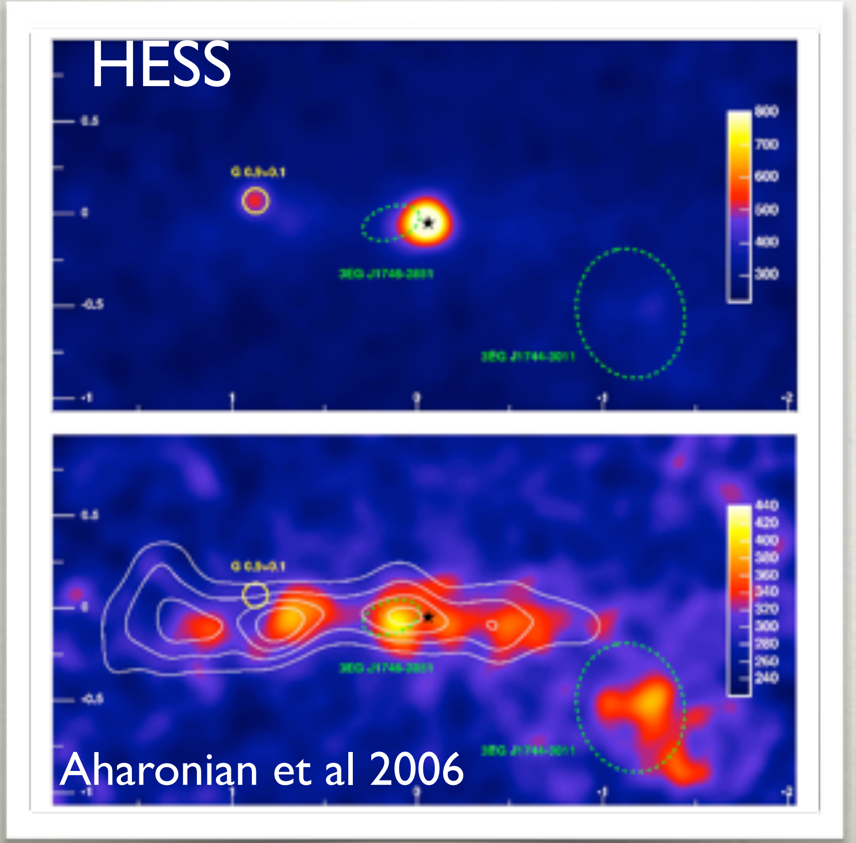
- source confusion: energetic sources near to or in the line of sight of the GC
- diffuse emission modeling: uncertainties in the integration over the line of sight in the direction of the GC, very difficult to model

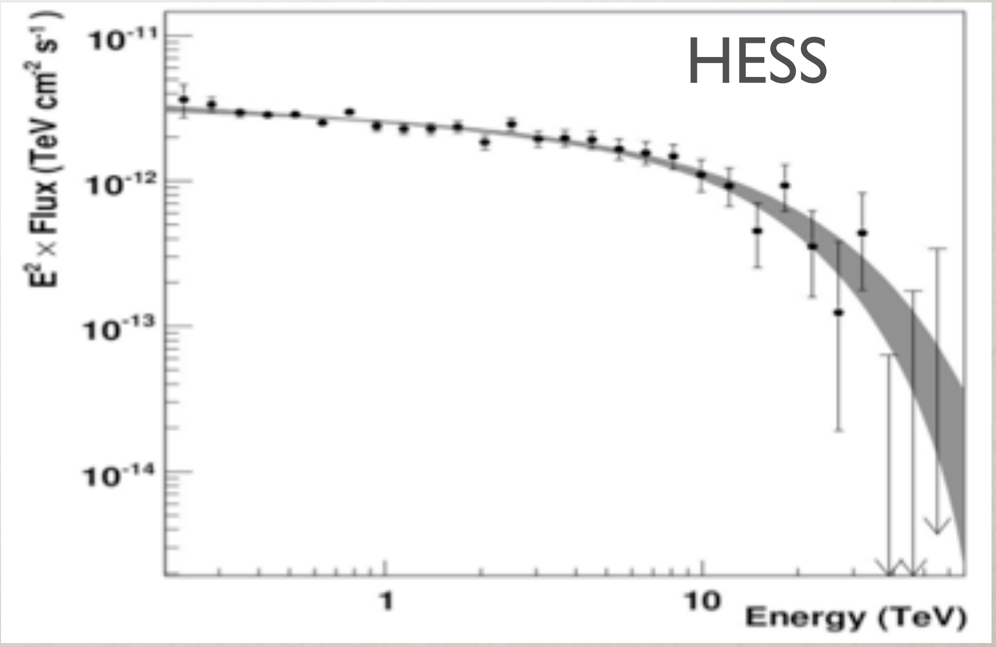


- High energy gamma-ray observations by Fermi, HESS, MAGIC, VERITAS

Galactic Center Region

- GC source: consistent spectrum observed by HESS (>100 hrs), MAGIC and VERITAS (~ 25 hrs, large zenith angle observations) compatible with astrophysical particle accelerators





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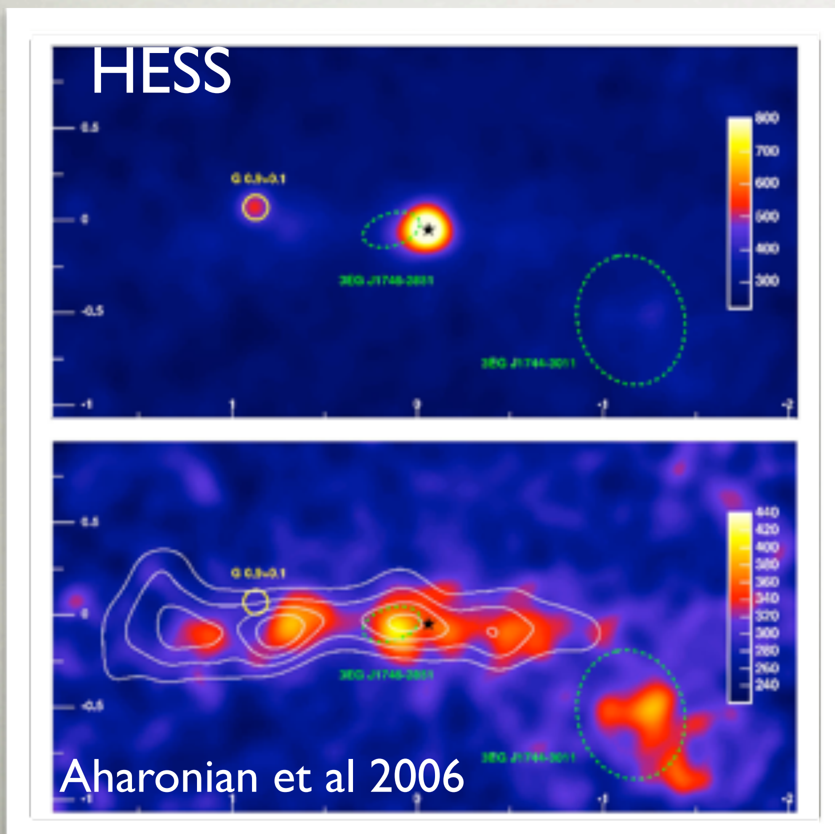

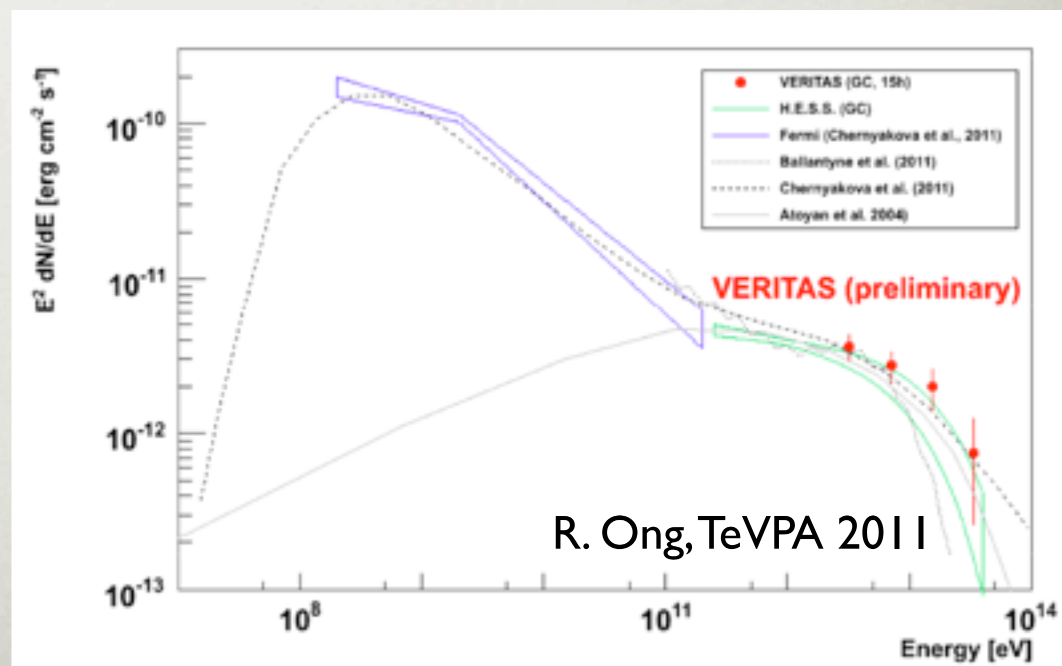

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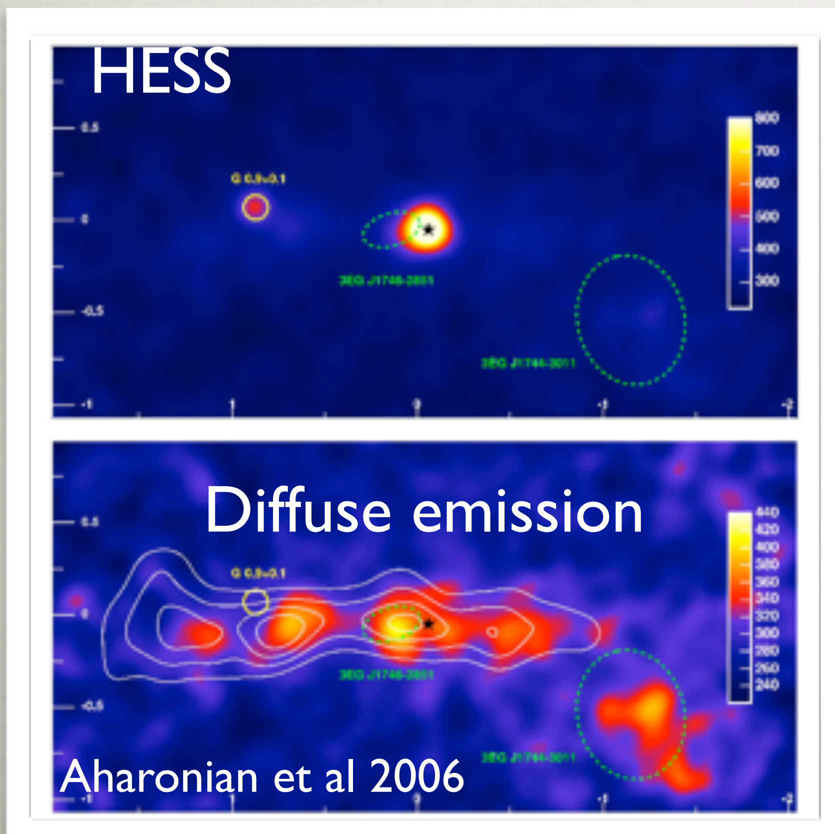
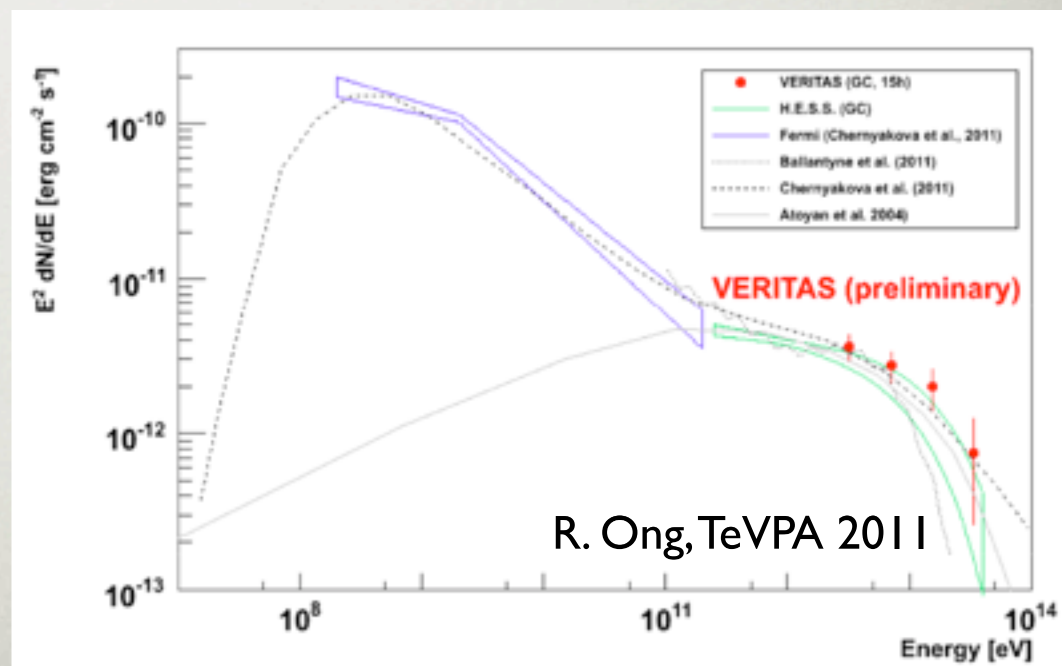
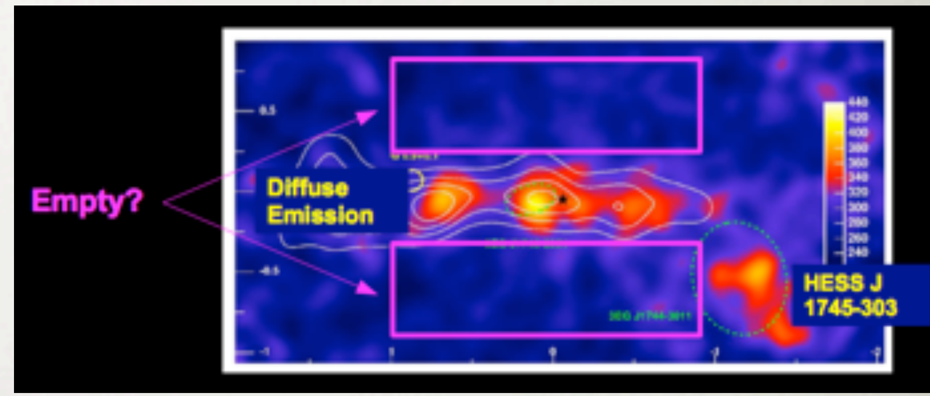
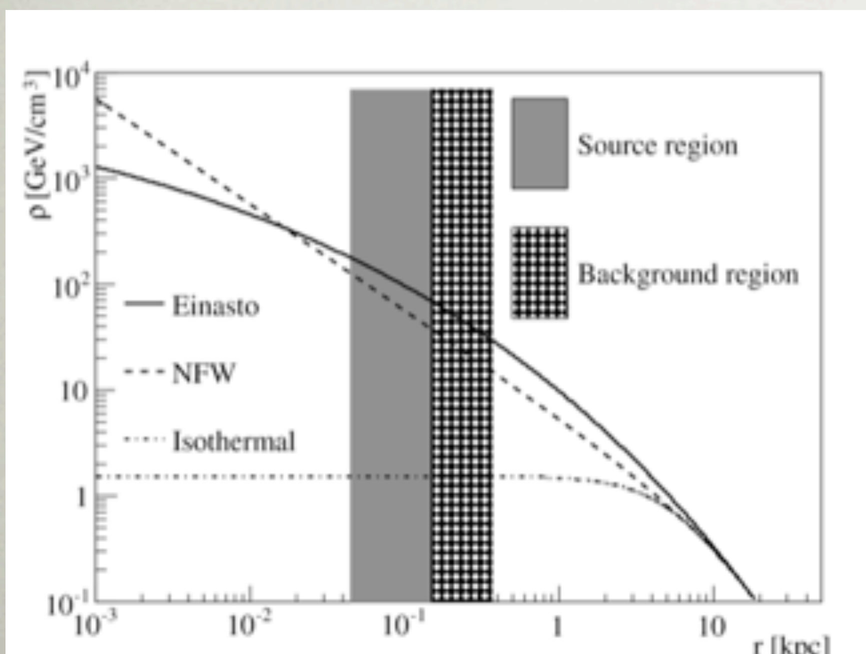




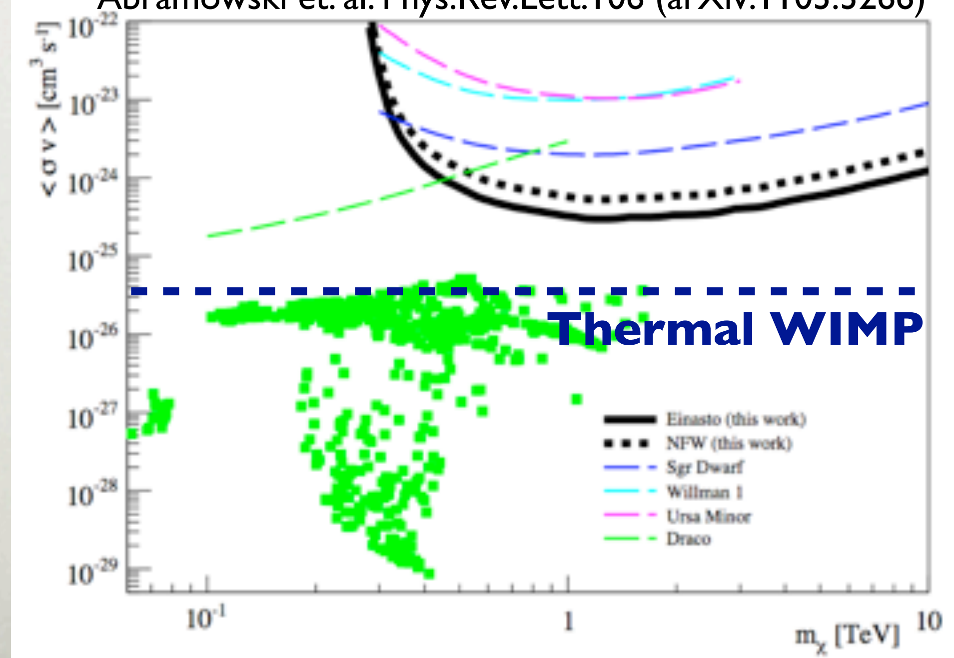
H.E.S.S.: Galactic Halo

- GC is complicated by astrophysics, look away from it!
- Signal region: relatively close to GC but "free" from astrophysical background
- Select a region where the contribution from DM is smaller for background subtraction (background region)
- Small dependence on DM profile





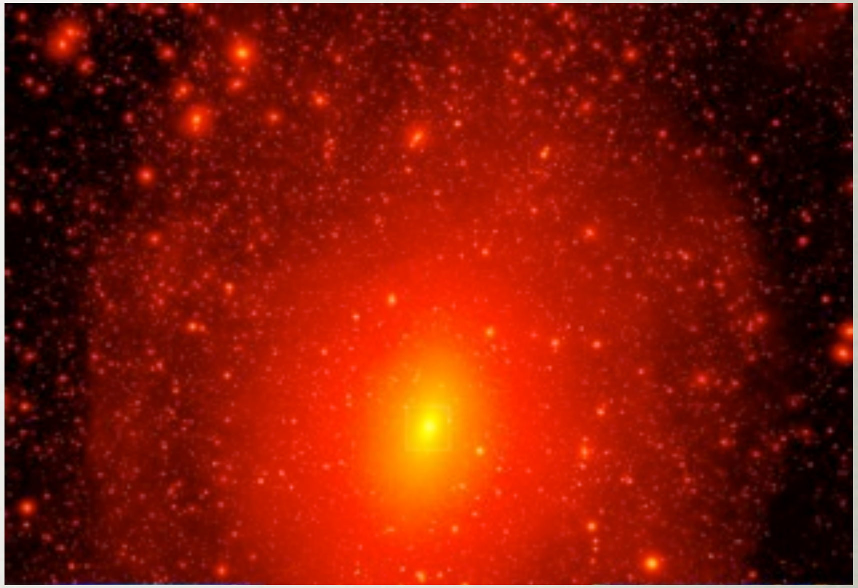
Abramowski et. al. Phys.Rev.Lett.106 (arXiv:1103.3266)

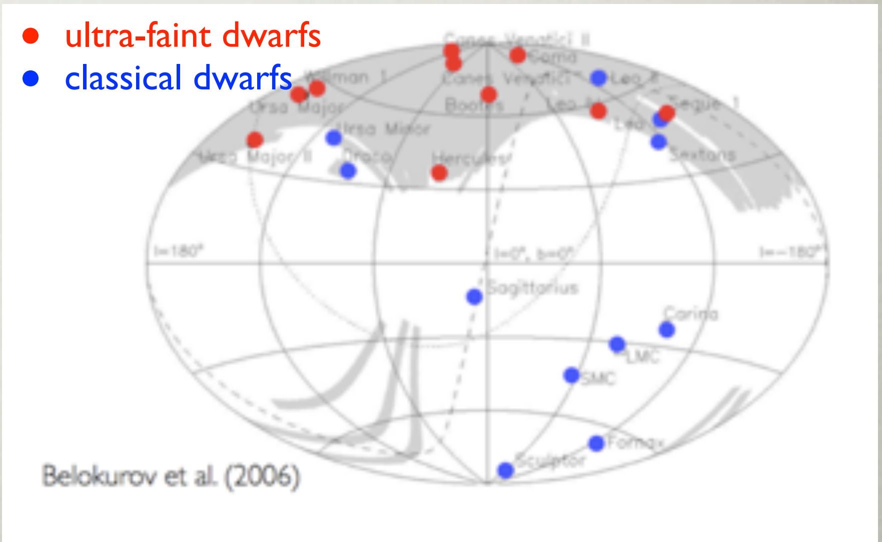


Dark Matter Substructures

- Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation.
  - Very large M/L ratio: 10 to ~> 1000 (M/L ~10 for Milky Way)
  - More promising targets could be discovered by current and upcoming experiments! (SDSS, DES, PanSTARRS, ...)
- Excellent targets for gamma-ray DM searches as most are expected to be free from other gamma ray sources and have low content in dust/gas, very few stars
- Select promising dSph for observations

➡ DM density inferred from the stellar data!





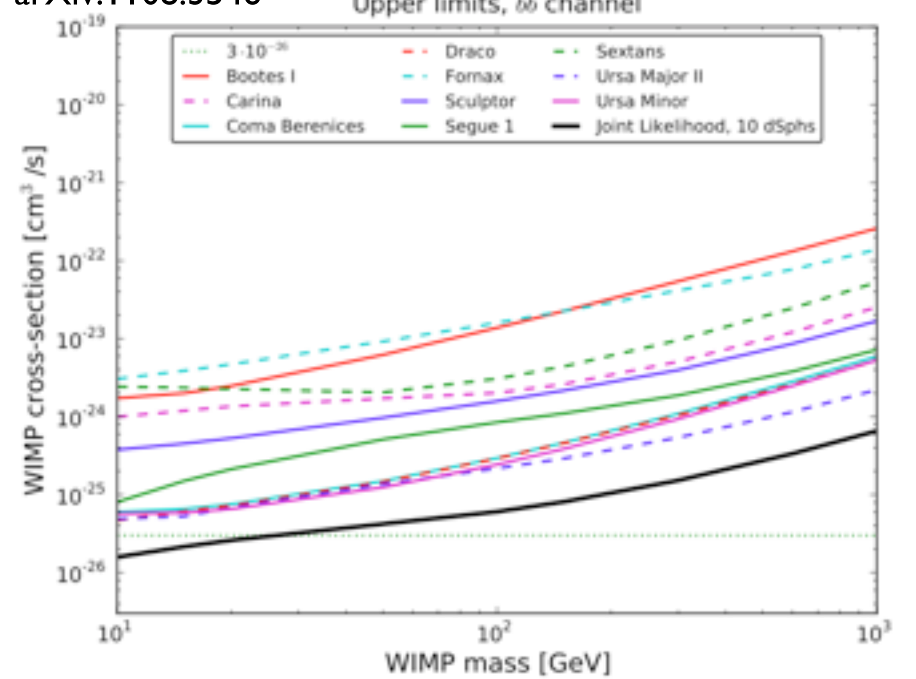
Fermi: Dwarf Spheroidals

- Selected dSph: Bootes I, Carina, Coma Berenices, Draco, Fornax, Sculptor, Segue I, Sextans, Ursa Major II, Ursa Minor

➡ No detection of dSph by Fermi with 2 years of data

- Determine 95% flux upper limits for several possible annihilation final states
- Combine with the DM density inferred from the stellar data (assume NFW profile) to set constraints on the annihilation cross section
- Constraints include systematic uncertainties on the DM content!

arXiv:1108.3546



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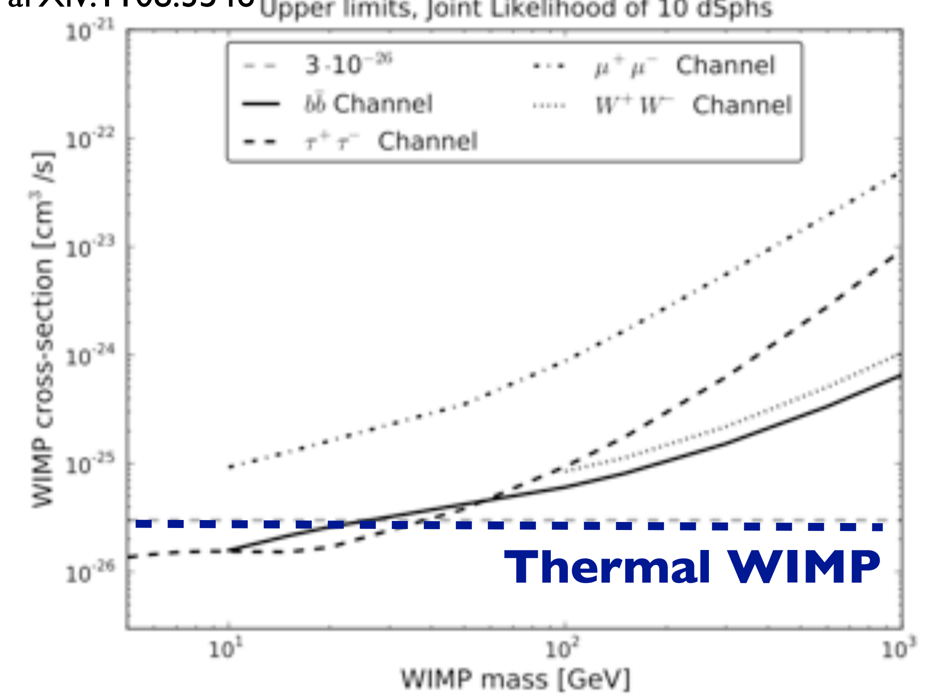

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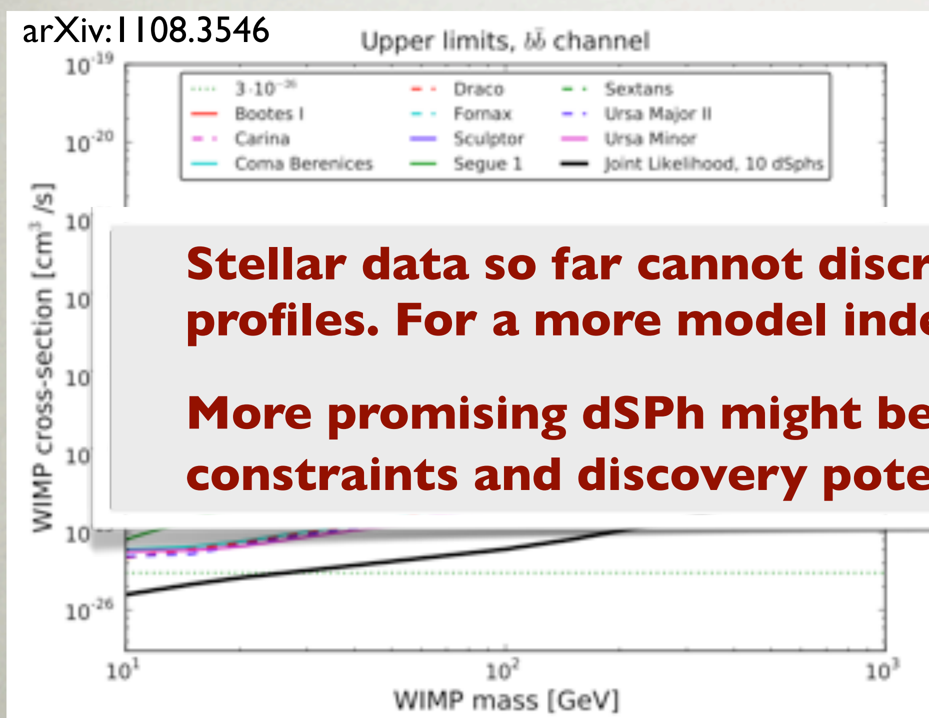
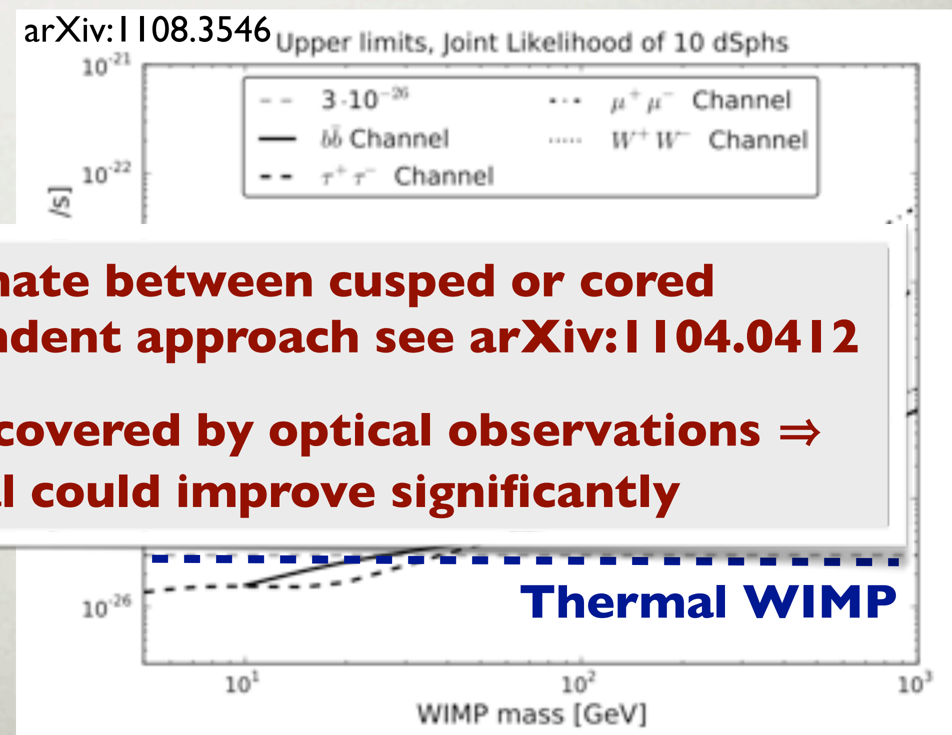


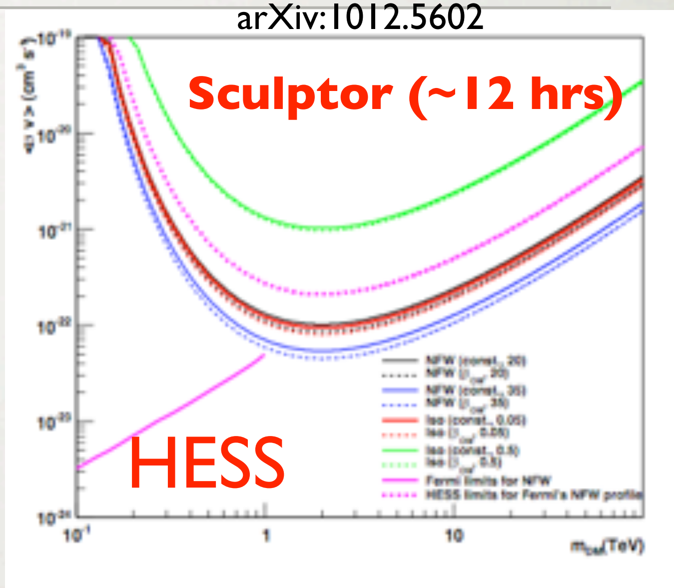


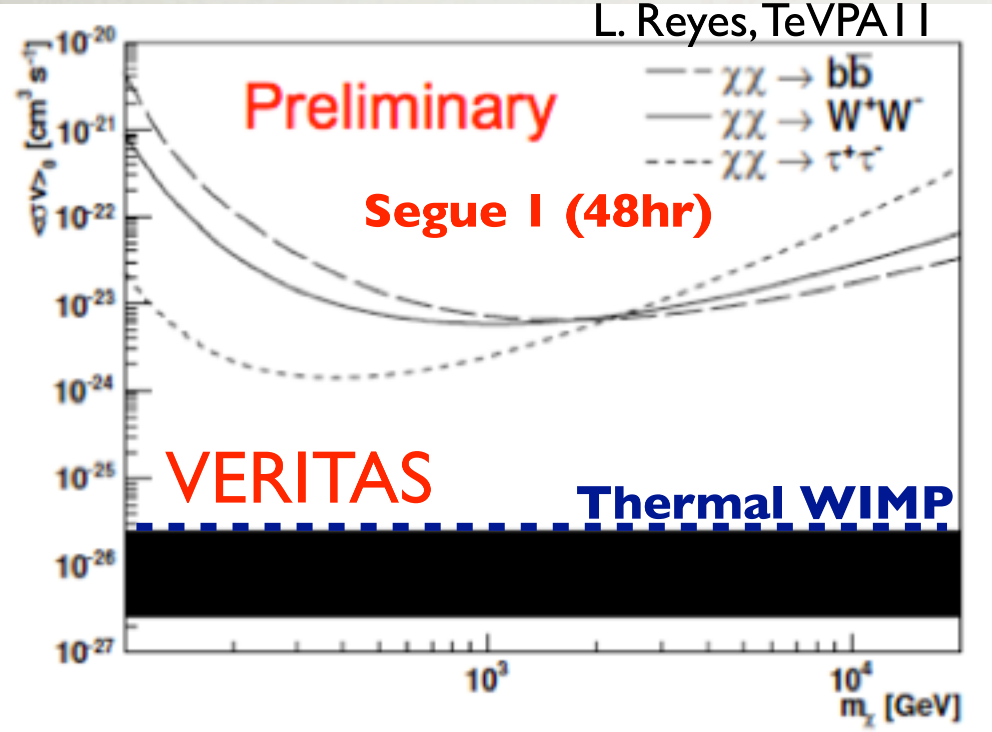
Stellar data so far cannot discriminate between cusped or cored profiles. For a more model independent approach see arXiv:1104.0412

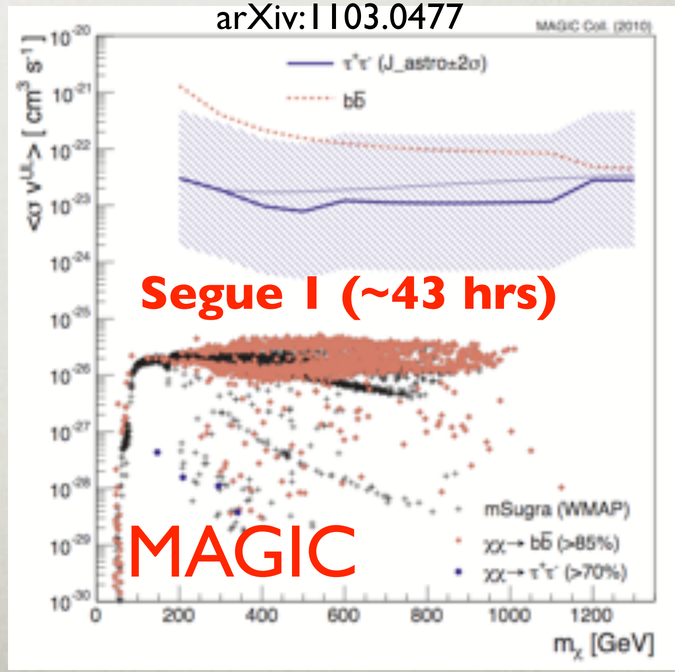
More promising dSPh might be discovered by optical observations ⇒ constraints and discovery potential could improve significantly

HESS, MAGIC, VERITAS: Dwarf Spheroidals

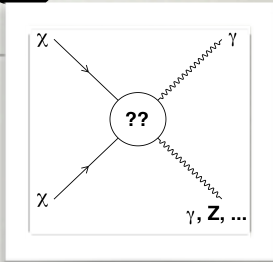
- Dedicated observations of a number of dwarf spheroidal galaxies
- ➡ No significant excess in any of the observations
- Set constraints on the annihilation cross section





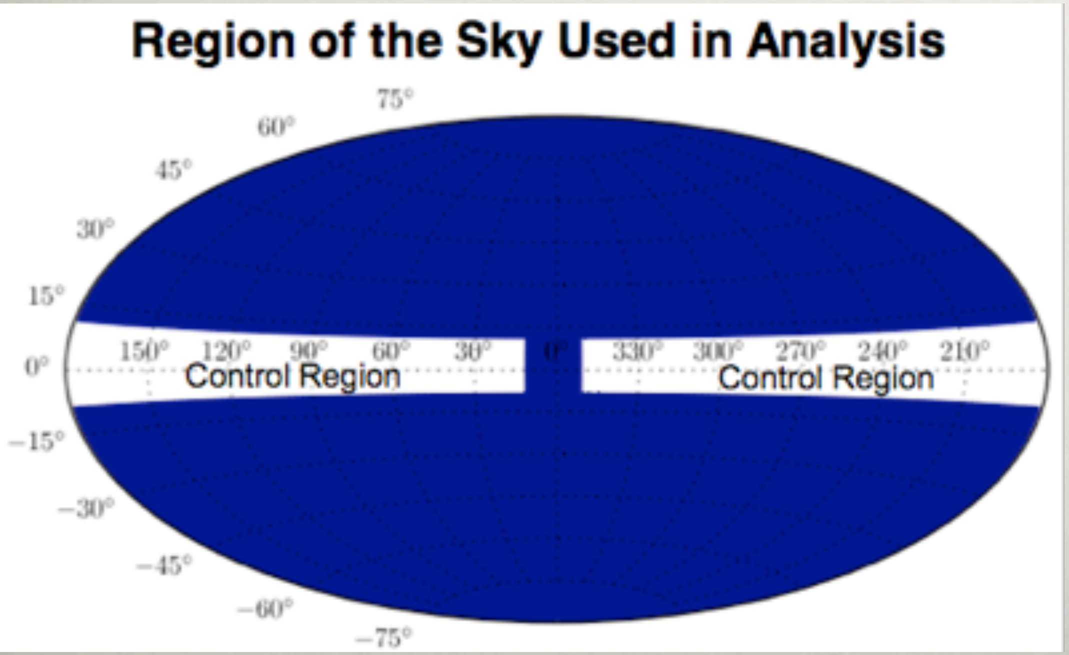


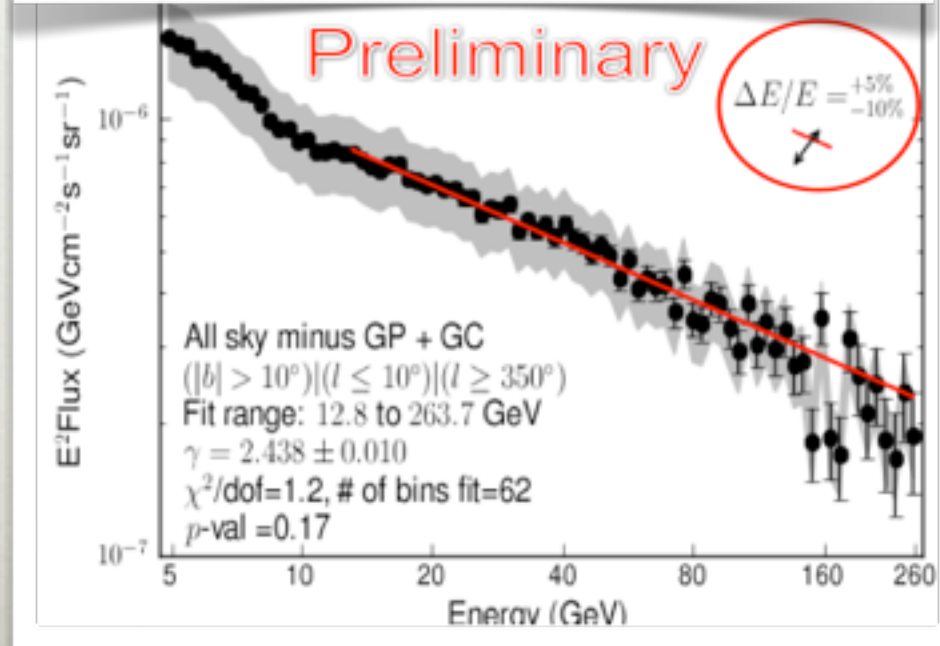
Fermi Search for Lines



- ☺ Smoking gun signal of dark matter.
- ☹ The line signal is generally suppressed (but enhanced in some models!)
- Search for lines in the first 23 months of Fermi data and include the data from most of the sky (remove point sources and most of the galactic disk)
- The signal is the LAT line response function. The background is modeled by a power-law function and determined by the fit ⇒ No astrophysical uncertainties.

Inclusive Photon Spectrum is a featureless power-law, index ~2.44 (13 < E < 264 GeV)



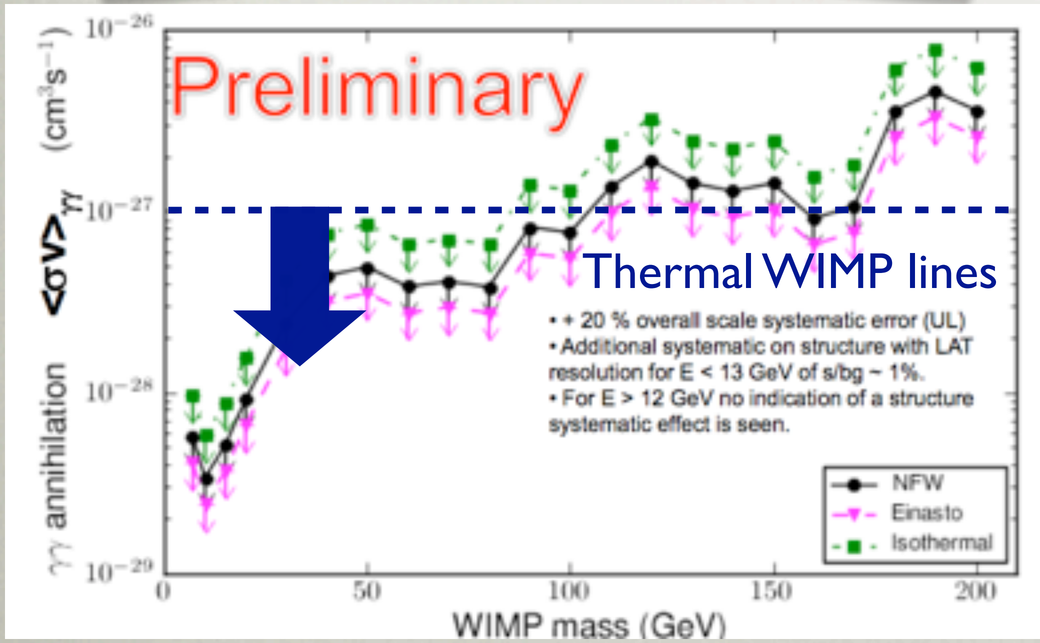


Fermi Search for Lines

➡ No line detection. 95% CL flux upper limits, 7-200 GeV energy range

- With assumptions on the dark matter density distribution, we extract constraints on the dark matter annihilation cross-section or decay lifetime

Might begin to constrain typical thermal WIMPs with M_{WIMP}<100 GeV



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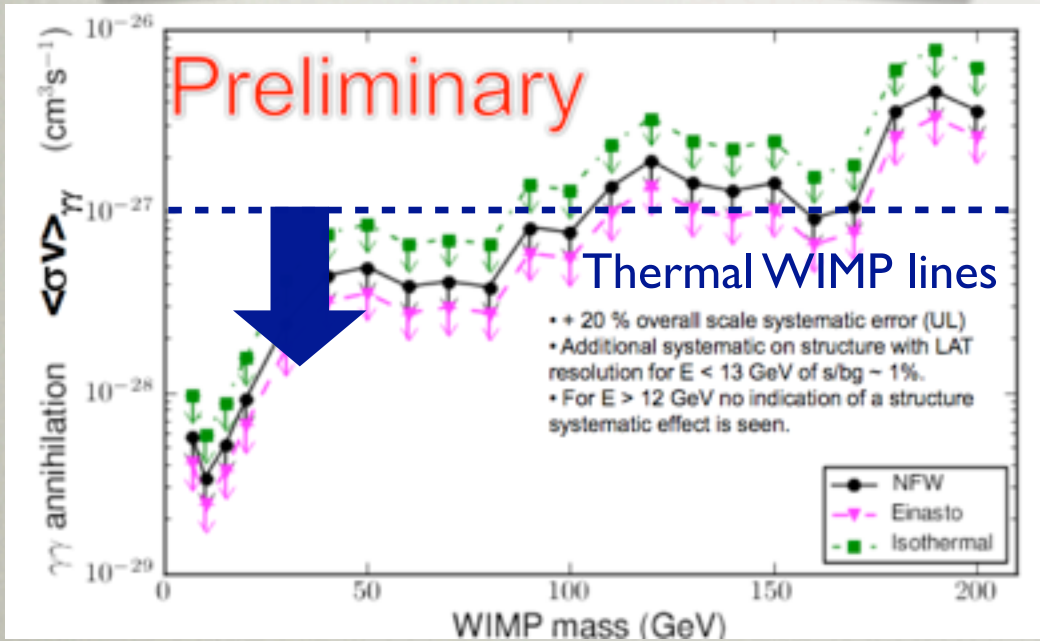
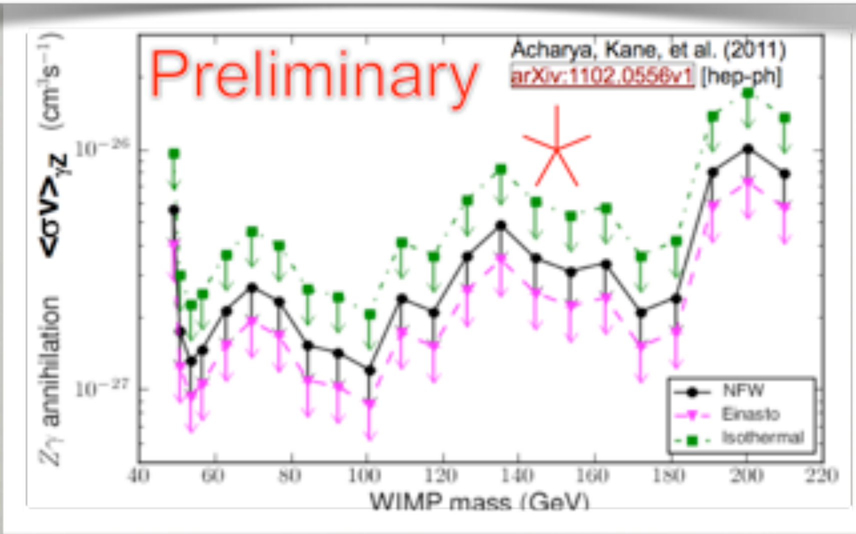
Limits also constrain theories with:
- non-thermally produced WIMPs. E.g. : Wino LSP
- models with enhanced lines
- decaying WIMPs with lifetimes < 10^{29} s





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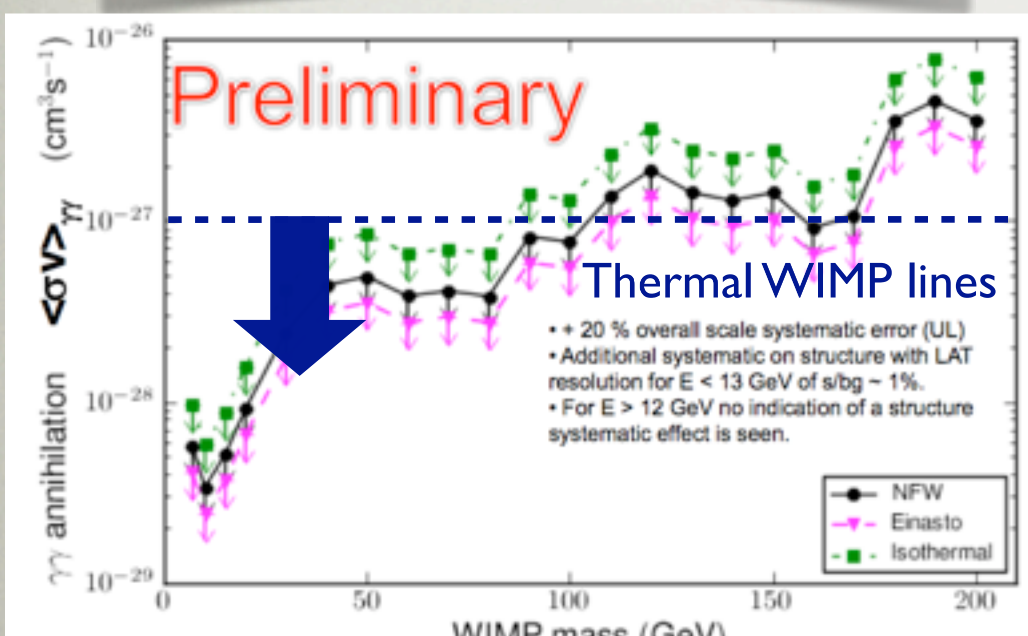

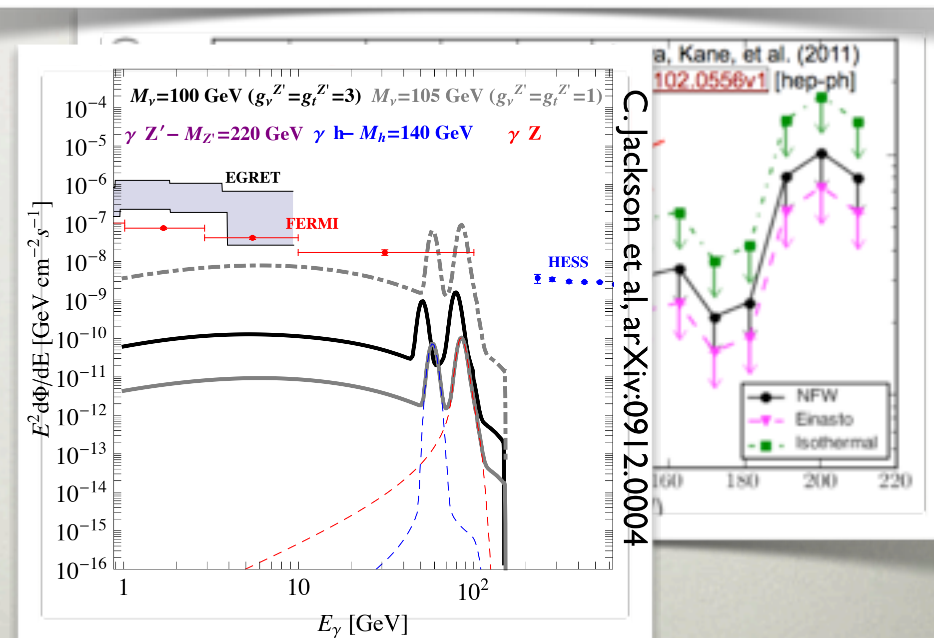

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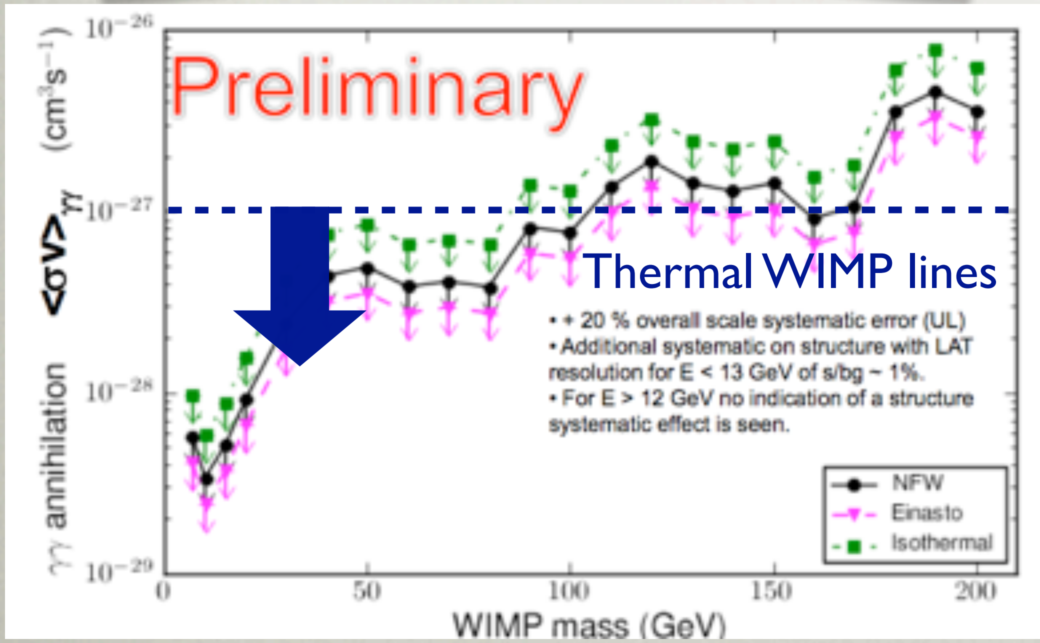
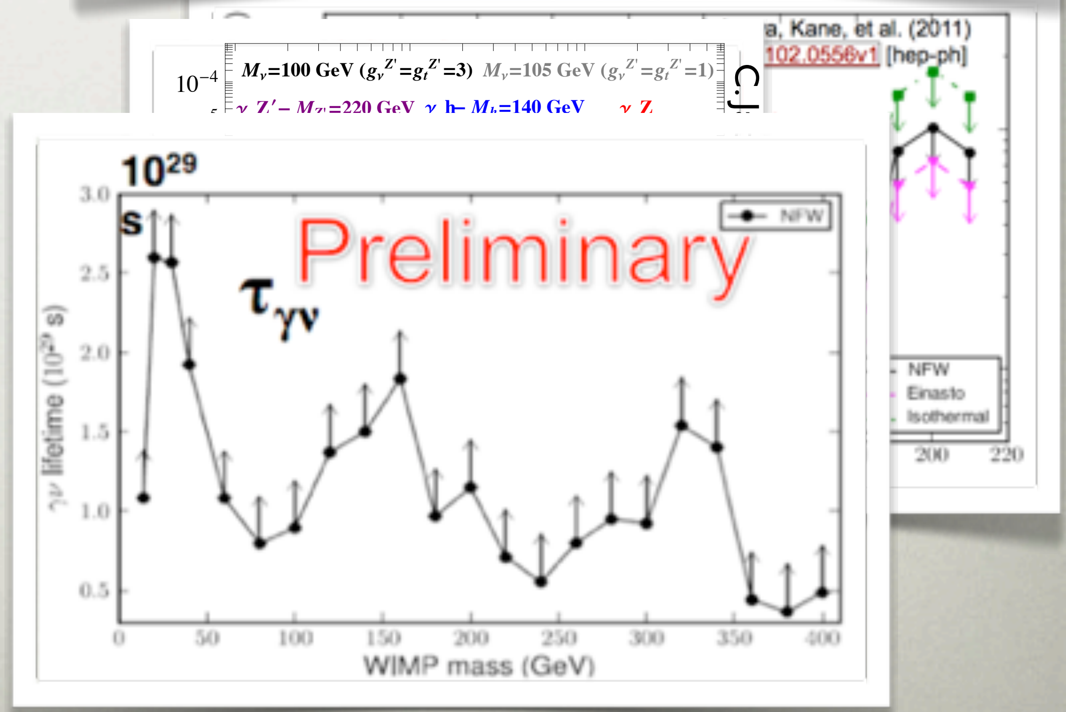
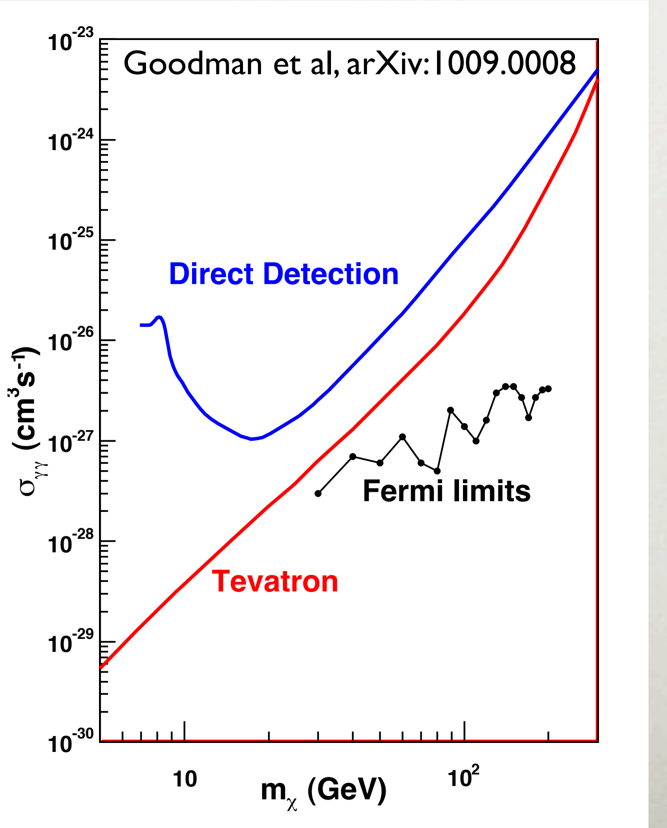
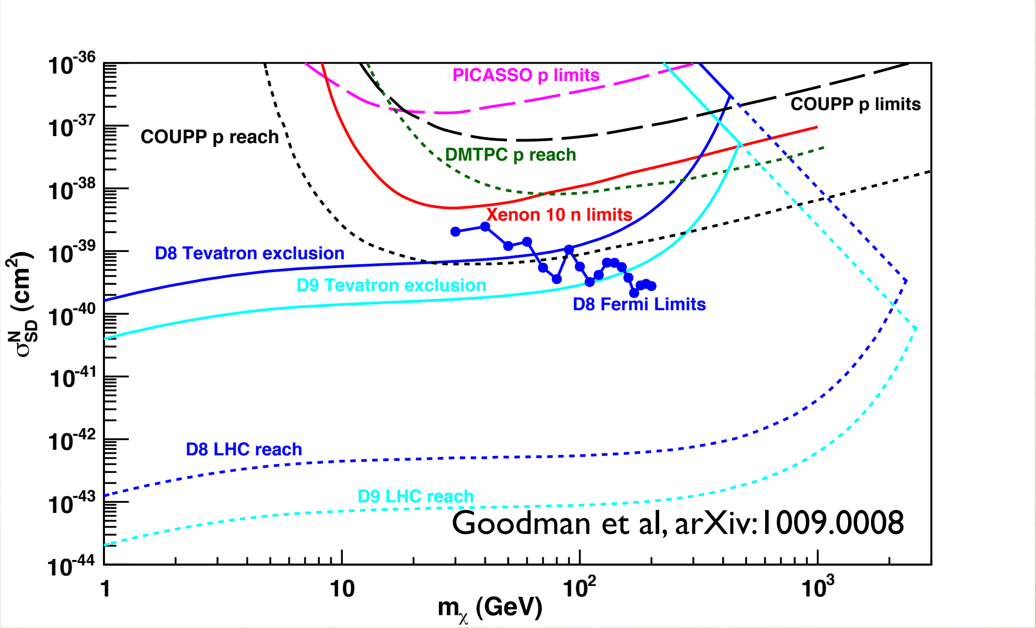




Model Independent Dark Matter Constraints

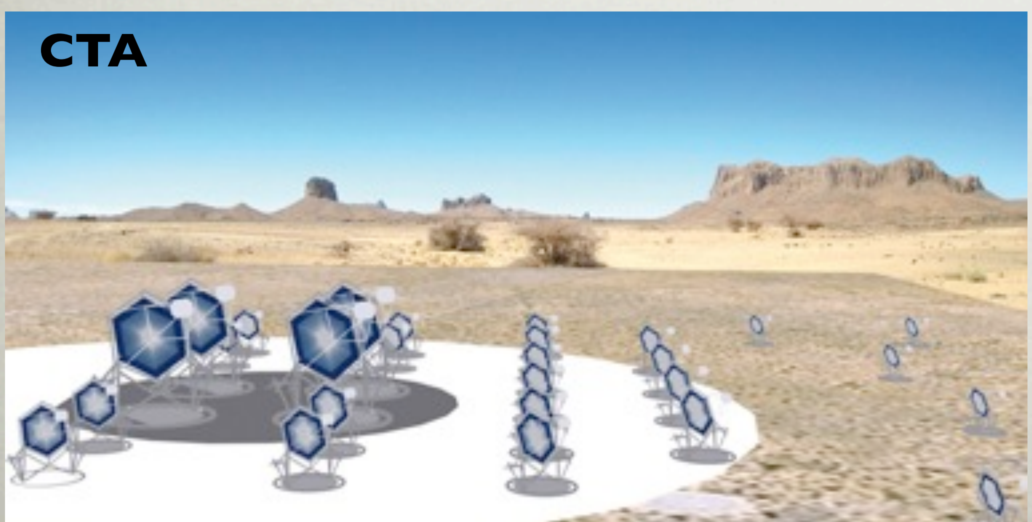
- Constraints on WIMPs are generally presented by assuming a specific underlying particle physics model (e.g. Supersymmetry, Extra Dimensions)
- If you don't have a favorite model, it is possible to express these constraints in a more model independent way by capturing all possible interactions in general categories. Most theories can be included in this type of formalism (effective theory)
- Fermi line constraints in the effective theory formalism compared to direct and collider searches:

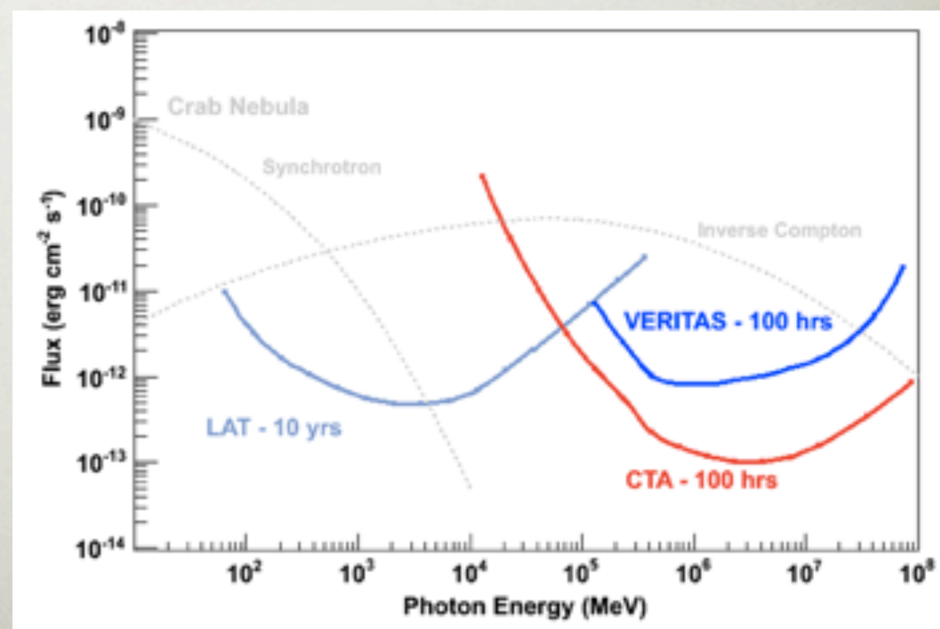




Gamma rays: Future Prospects

- Next generation gamma-ray observatories: Major Atmospheric Cherenkov Experiment (MACE; Hanle, India), Cherenkov Telescope Array (CTA)
- CTA:
  - Basic design: small core of large telescopes, surrounded by mid size telescopes and an outer ring of small telescopes
  - Improve sensitivity of current ACTs (~10x), extend to lower and higher energies (~10s GeV to >100 TeV).





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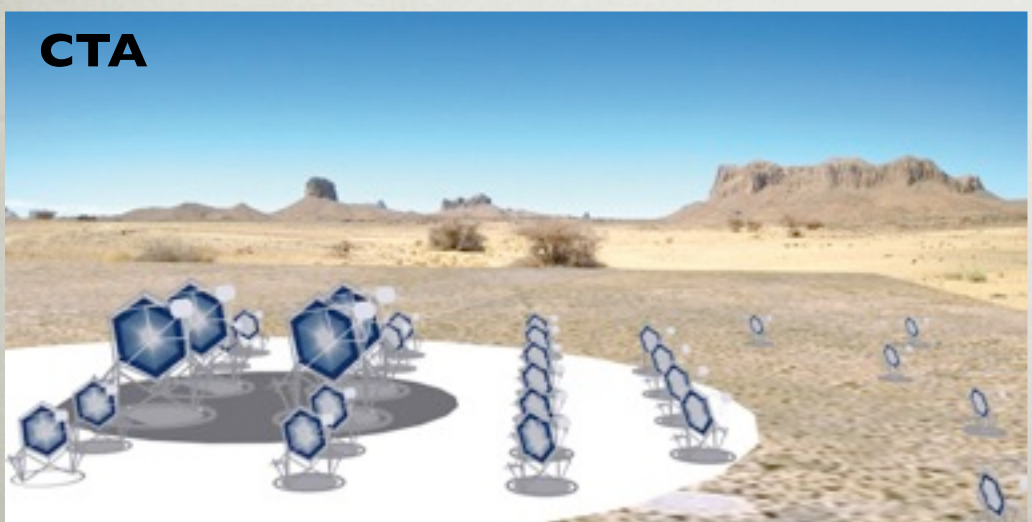
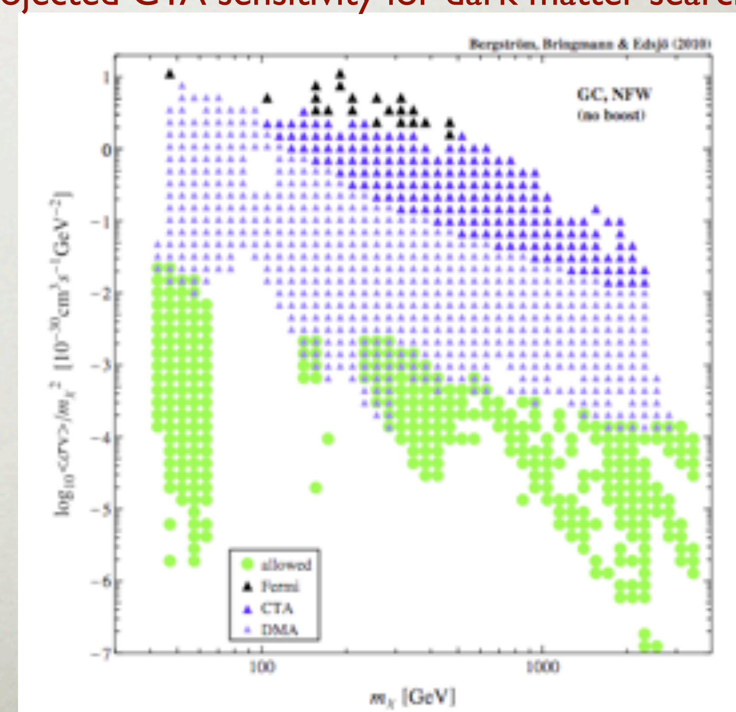
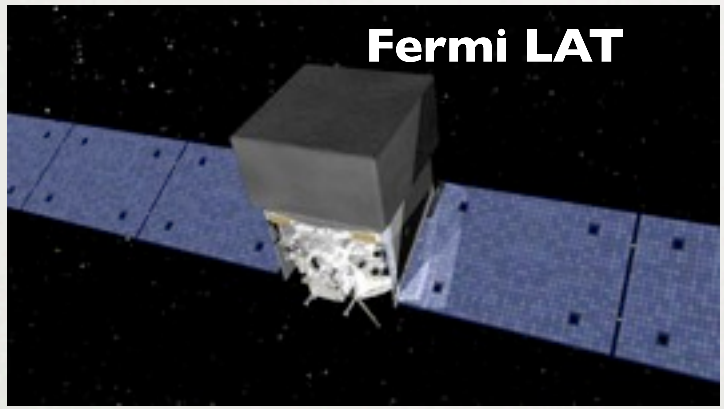


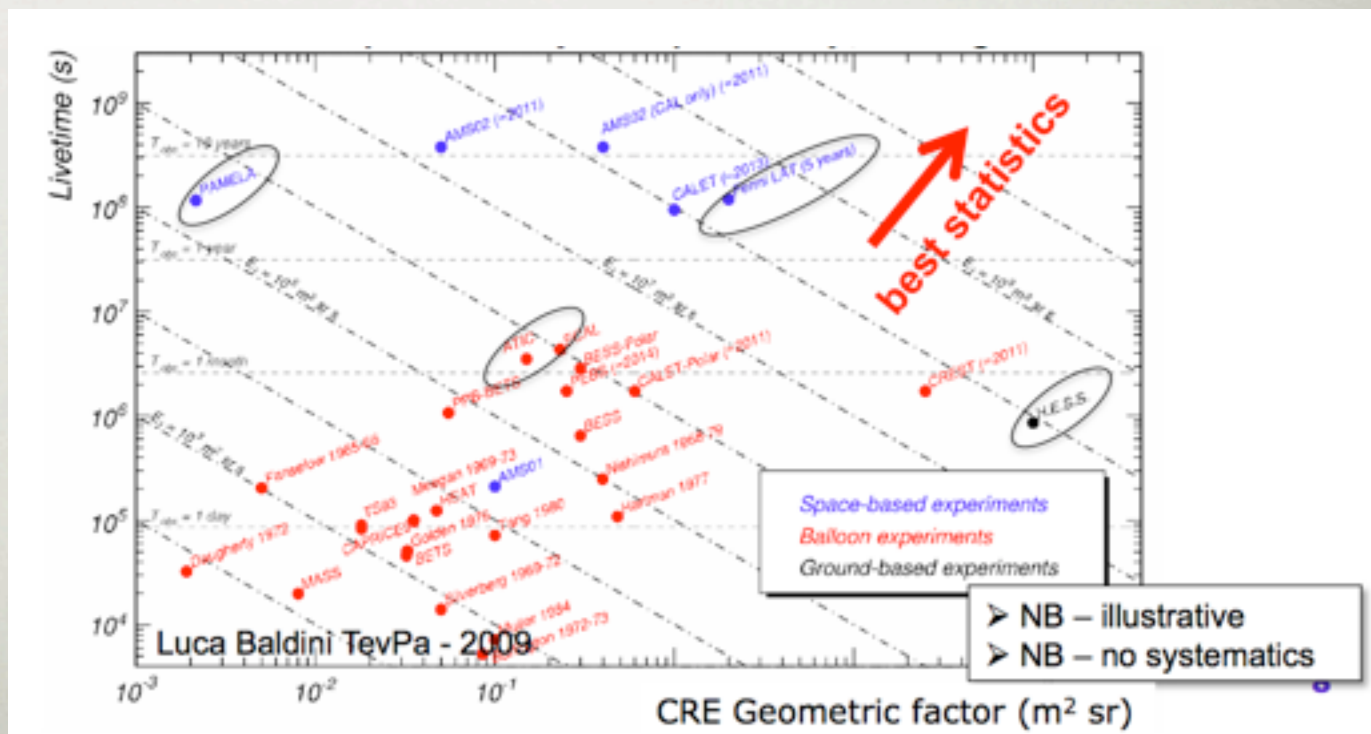
Projected CTA sensitivity for dark matter searches



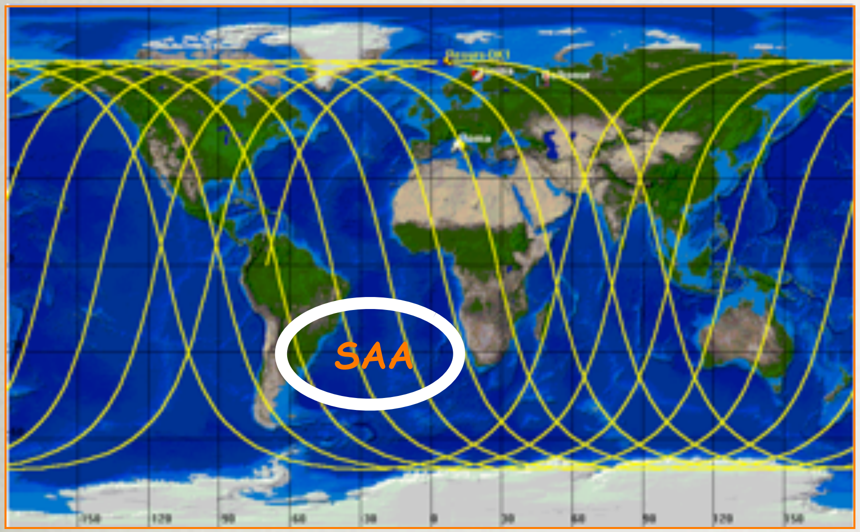
Cosmic rays


PAMELA


Fermi LAT


Livetime (s)
CRE Geometric factor (m² sr)
best statistics
PAMELA
H.E.S.S.
Space-based experiments
Balloon experiments
Ground-based experiments
Luca Baldini TevPa - 2009
➢ NB – illustrative
➢ NB – no systematics

PAMELA



Low-earth elliptical orbit

350 – 610 km

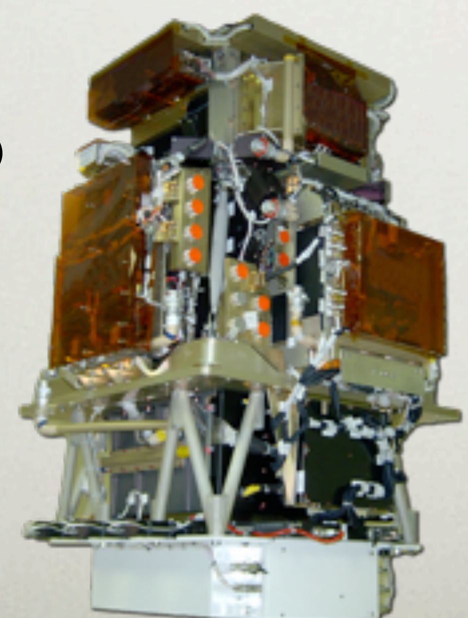
Quasi-polar (70° inclination)

SAA crossed

GF ~21.5 cm^{2}sr

Mass: 470 kg

Size: 130x70x70 cm^3

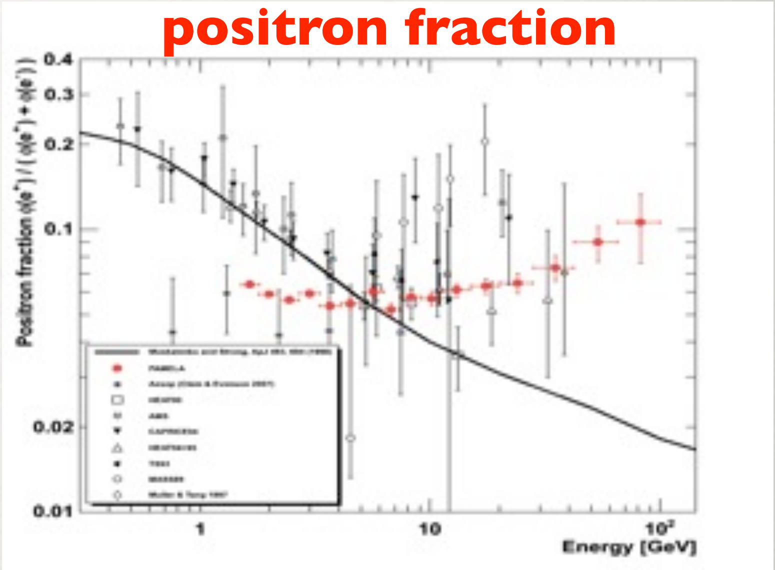


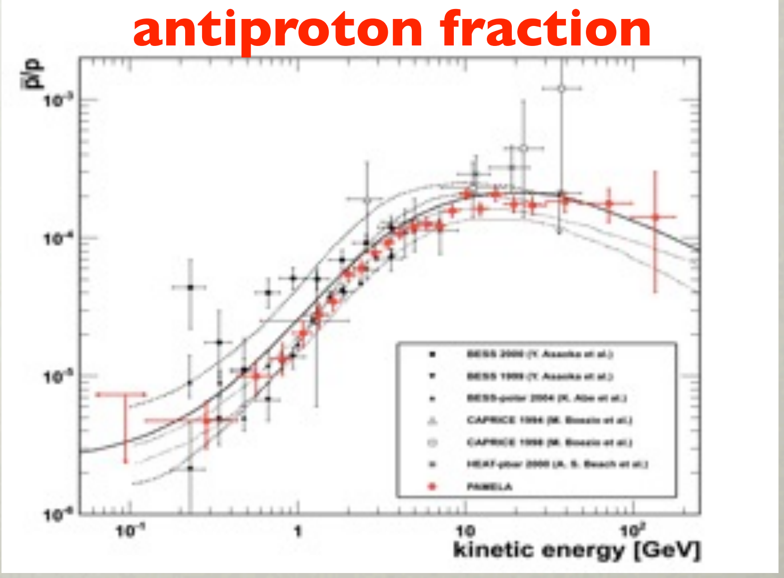
Design Performance

	Energy range
Antiprotons	80 MeV - 190 GeV
Positrons	50 MeV - 300 GeV
Electrons	up to 800 GeV
Protons	up to 1 TeV
Helium	up to 400 GeV/n
Electrons+positrons	up to 2 TeV (by calorimeter)
Light Nuclei (Li/Be/B/C)	up to 200 GeV/n
AntiNuclei search	sensitivity of 3×10^{-8} in He/He

Electrons and Positrons

- While the measurement of the antiproton fraction in cosmic rays by PAMELA is in agreement with secondary production predictions, the positron fraction unexpectedly raises at high energy!





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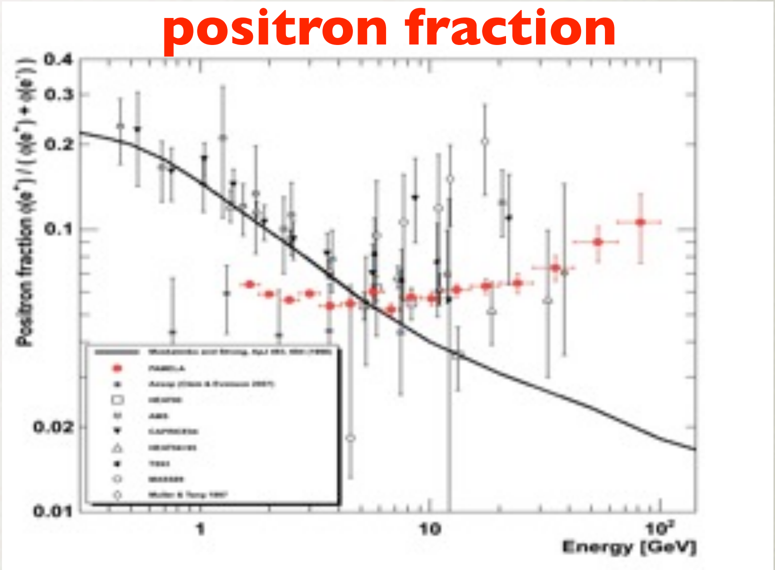
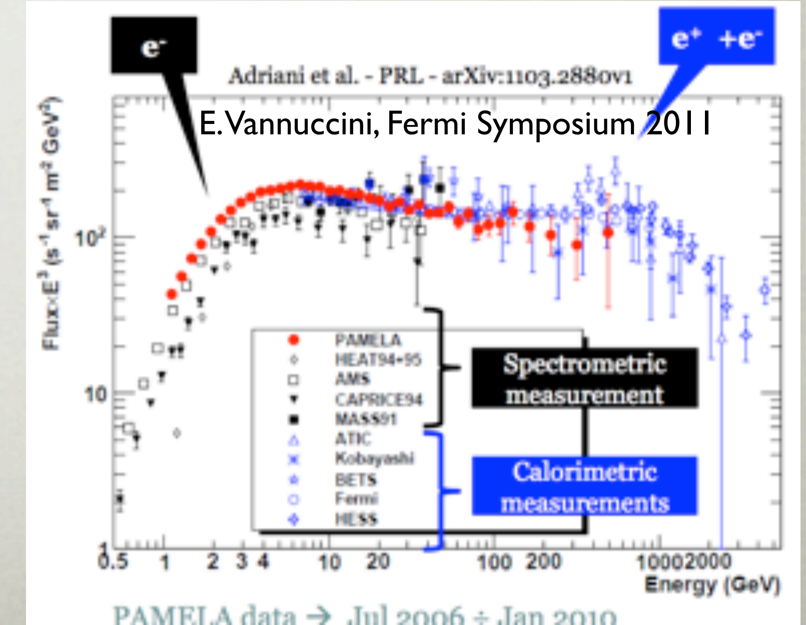
- PAMELA electron spectrum is consistent, within uncertainties, both with Fermi (and ATIC) measurement and with a raising positron contribution





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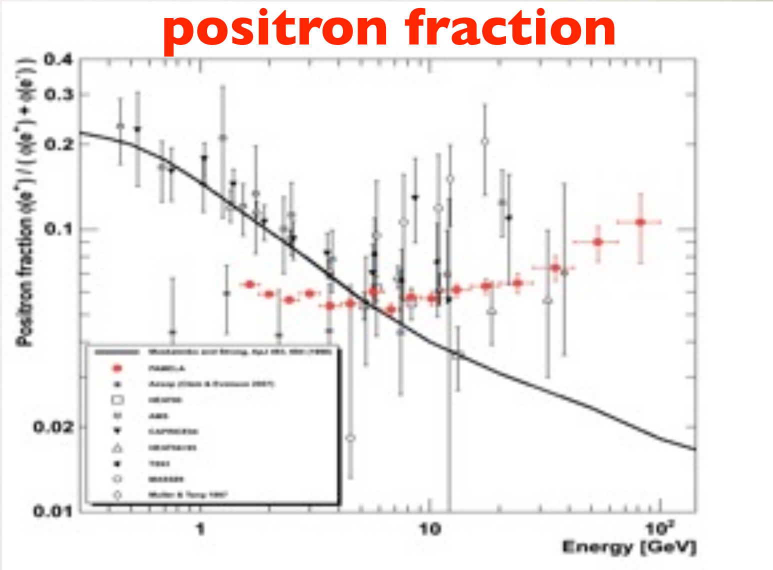
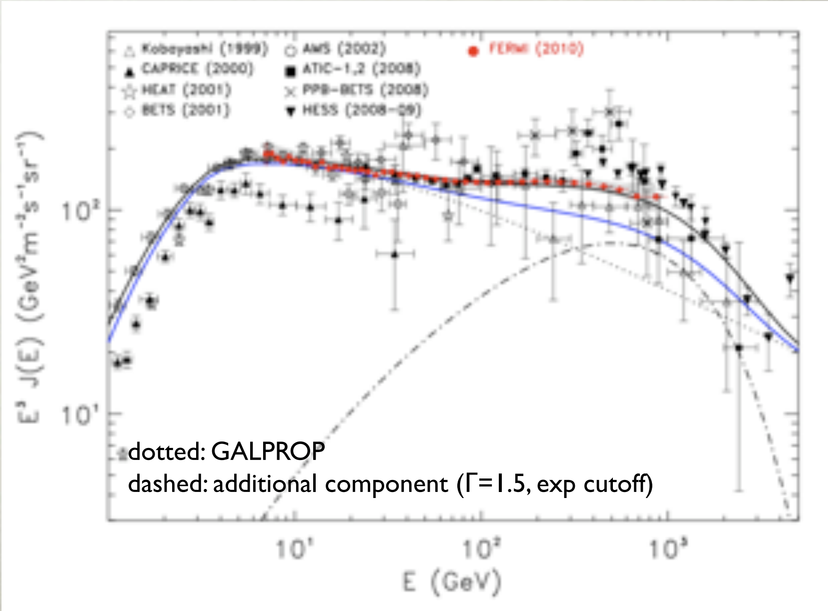


- PAMELA electron spectrum is consistent, within uncertainties, both with Fermi (and ATIC) measurement and with a raising positron contribution

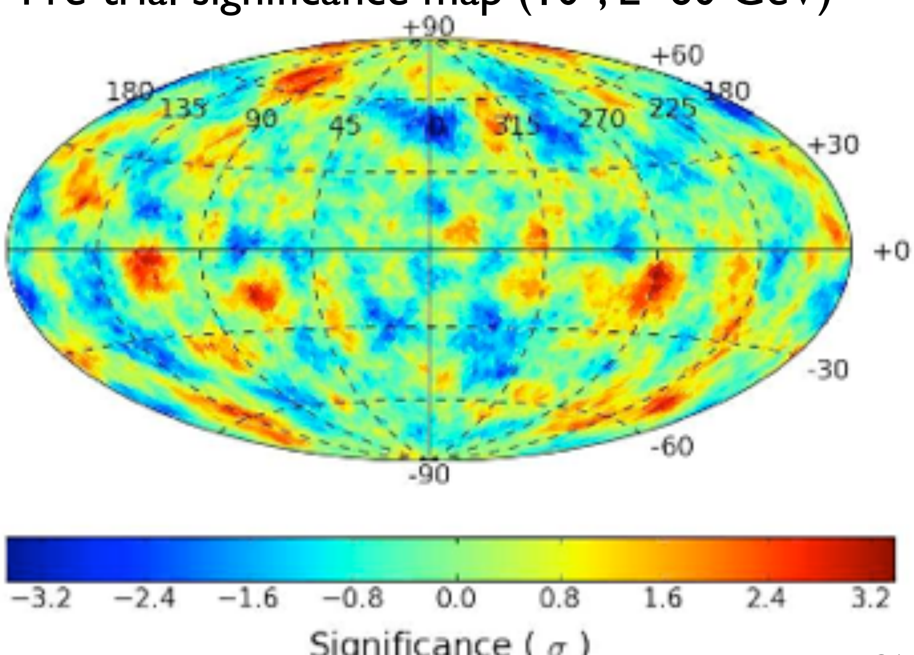
- Adding a new component (nearby source of e^+e^-) fits the PAMELA (electron and positron fraction) and Fermi ($e^+ + e^-$) data well.

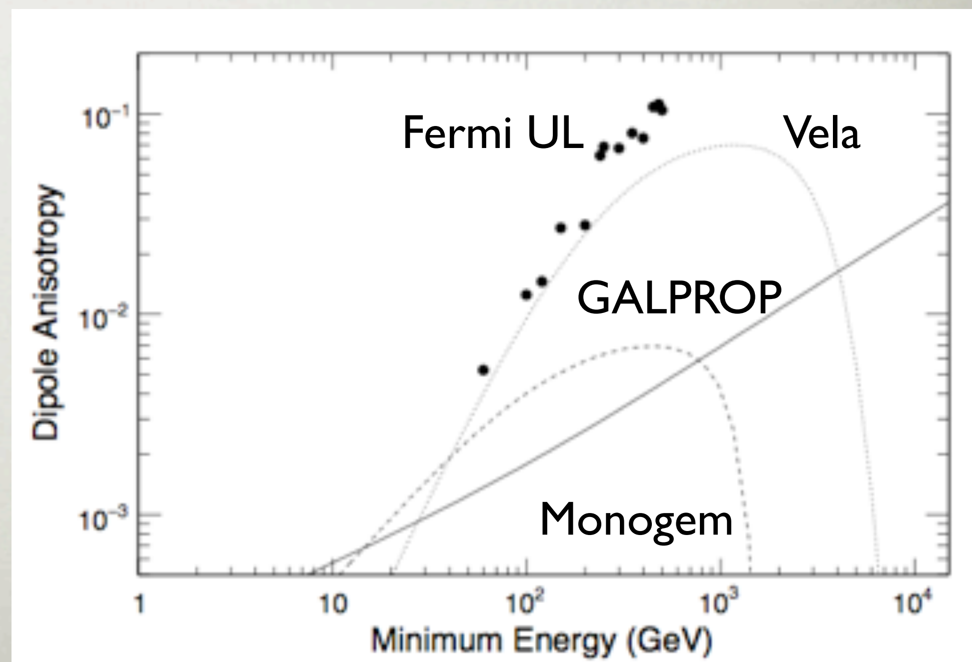


Fermi Electrons

- Fermi can test the nearby source hypothesis looking for anisotropies in the $e^{+} + e^{-}$ sky
  - No significant anisotropies were found in Fermi electron data (angular scales from 10° to 90°)
  - However upper limits on dipole anisotropy cannot yet rule out individual pulsar/DM interpretation of PAMELA and Fermi $e^{+}e^{-}$ data

Pre-trial significance map (10°, E>60 GeV)

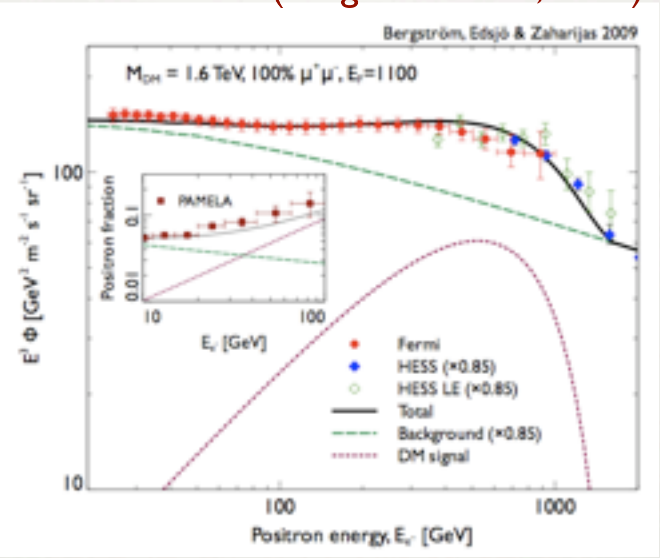




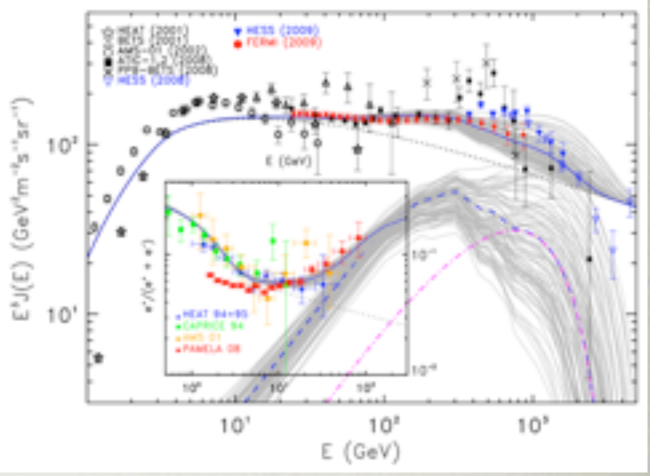
Could it Be Dark Matter?

Dark matter can reproduce the raise in the positron fraction, but several other explanations exists!

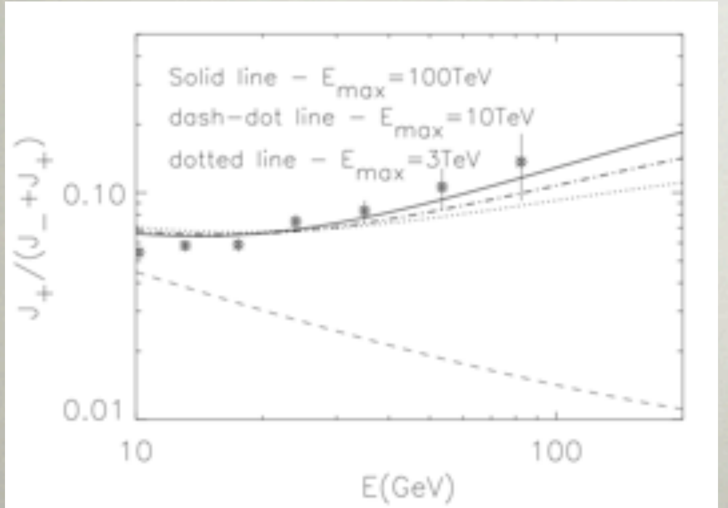
DM annihilation (Bergstrom et al, 2009)



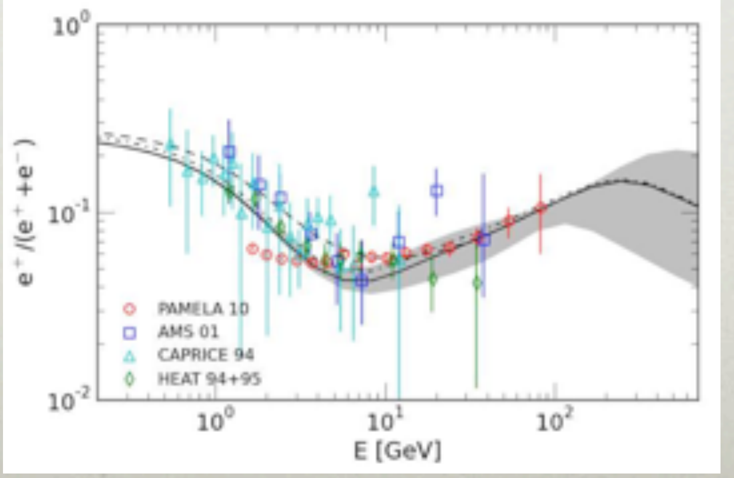
Pulsars (Grasso et al, 2011)



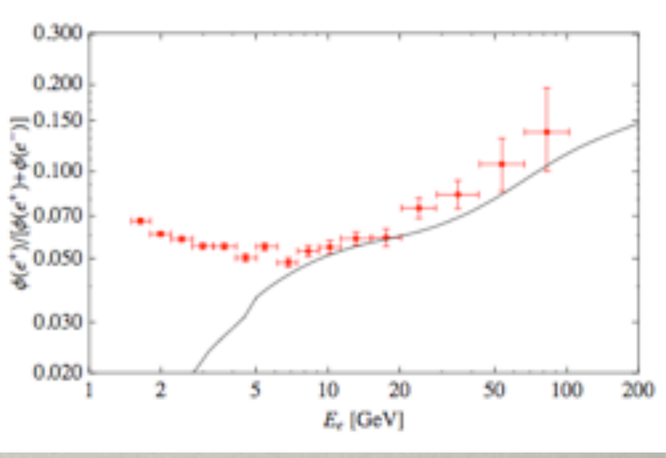
Production of secondary positrons at CR acceleration site, e.g. SNR (Blasi 2009)



Injection model based on gamma ray observations (S.-H. Lee, T. Kamae et al, 2010)

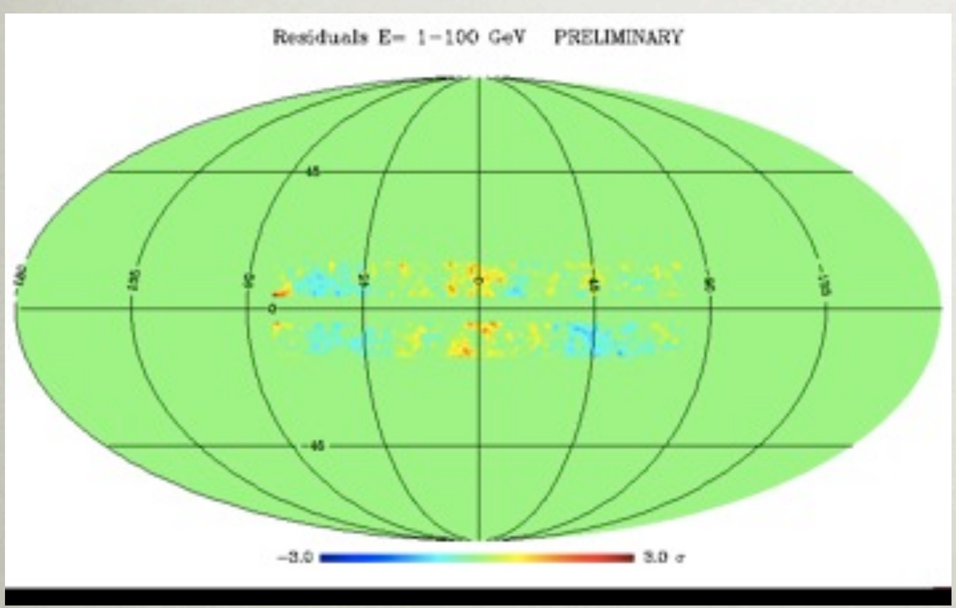


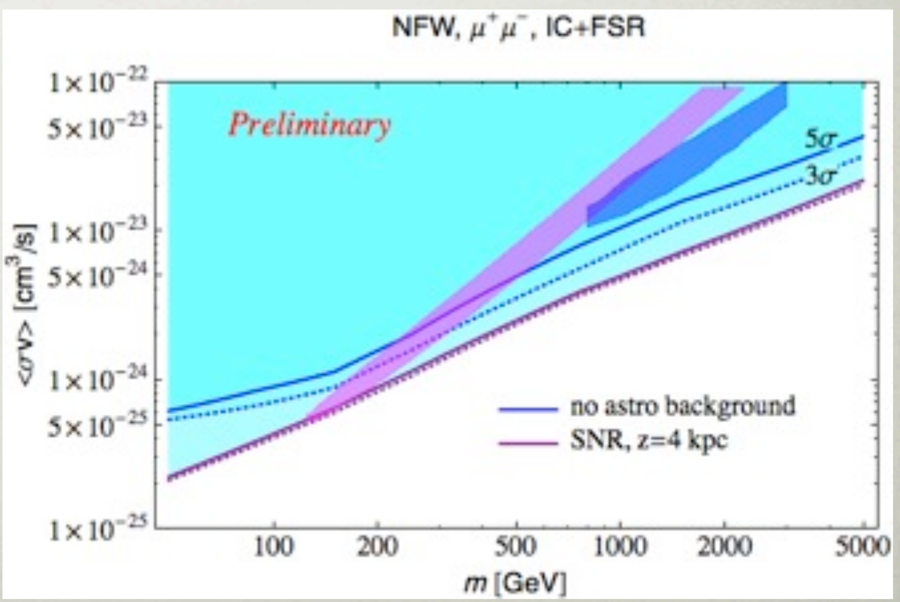
Klein-Nishina suppression of the IC cooling rate (Stawarz et al, 2009)



Could it Be Dark Matter?

- Can constrain dark matter interpretation of CR e^+e^- with gamma rays, e.g. Fermi's galactic halo
- Limit the analysis to regions of the galactic halo better described by the model
- Require that a DM contribution does not over-predict the data in these regions

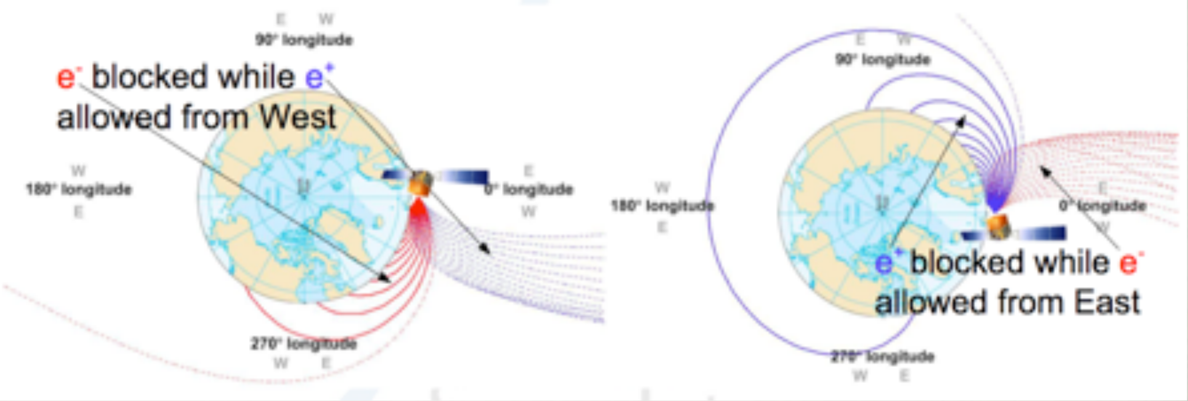


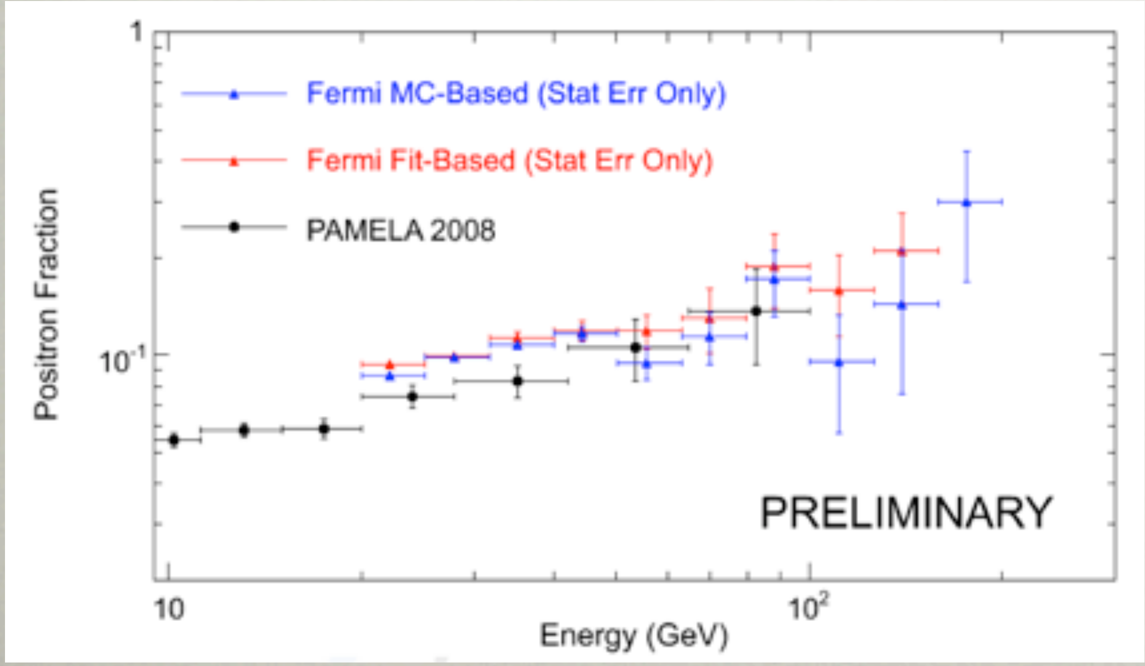


FERMI POSITRONS

➡ Use the Earth magnetic field to separate electrons and positrons!

- Some regions of the sky (which depend on the energy of the particle and the Fermi position in the orbit) are be blind to electrons or positrons due to shadowing from the Earth





➡ Consistent with rise observed by PAMELA. Rise confirmed up to 200 GeV.

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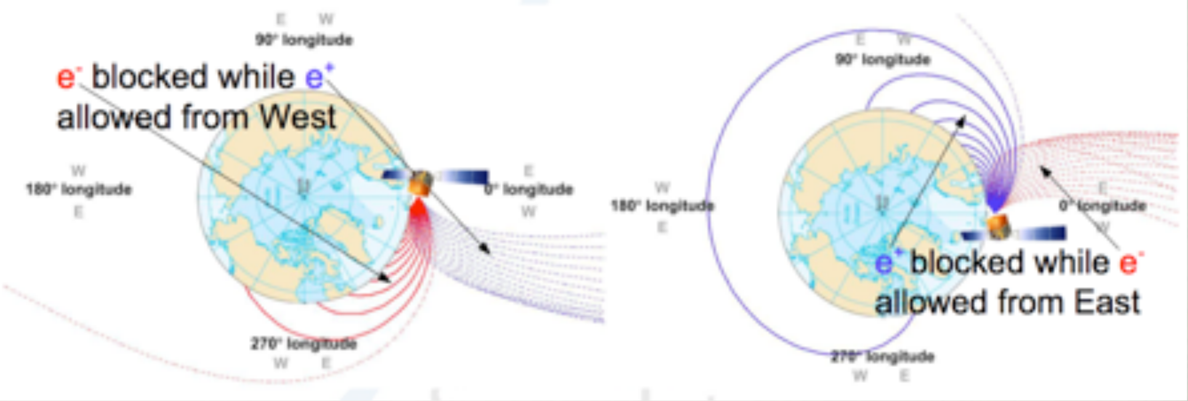

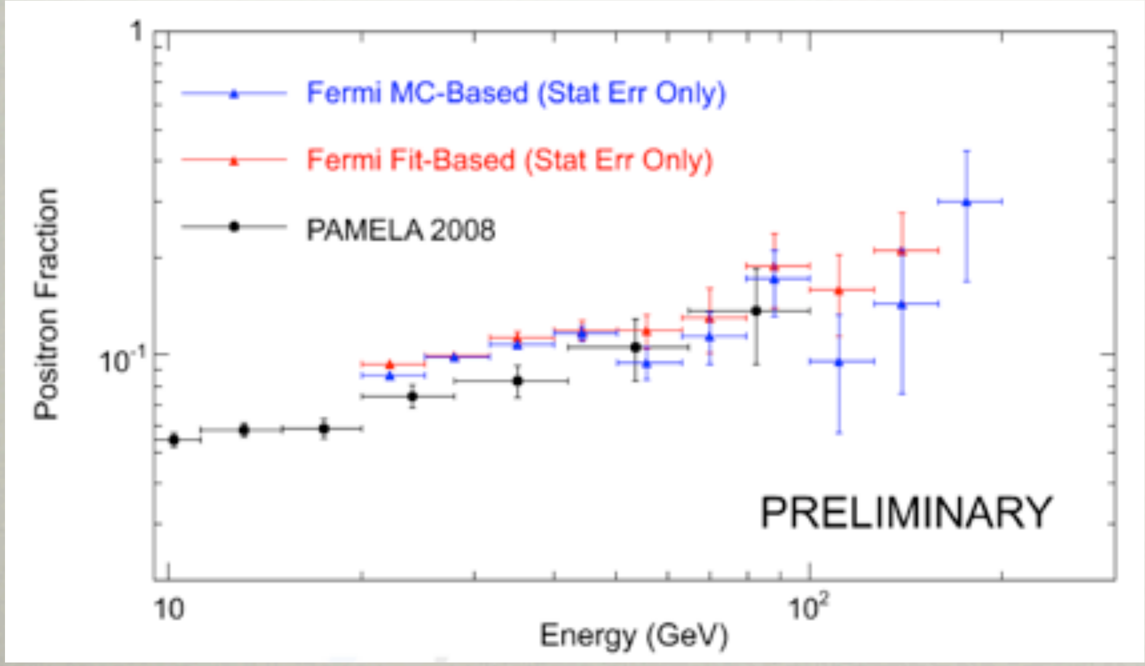

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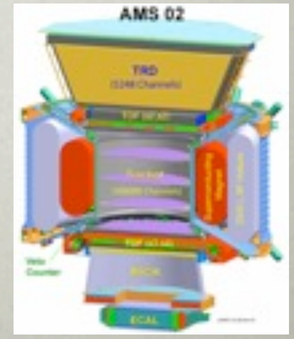
Waiting for AMS data!



Neutrinos: IceCube

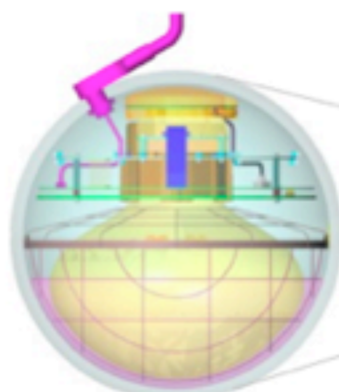
IceCube

5160 DOMs on 86 strings

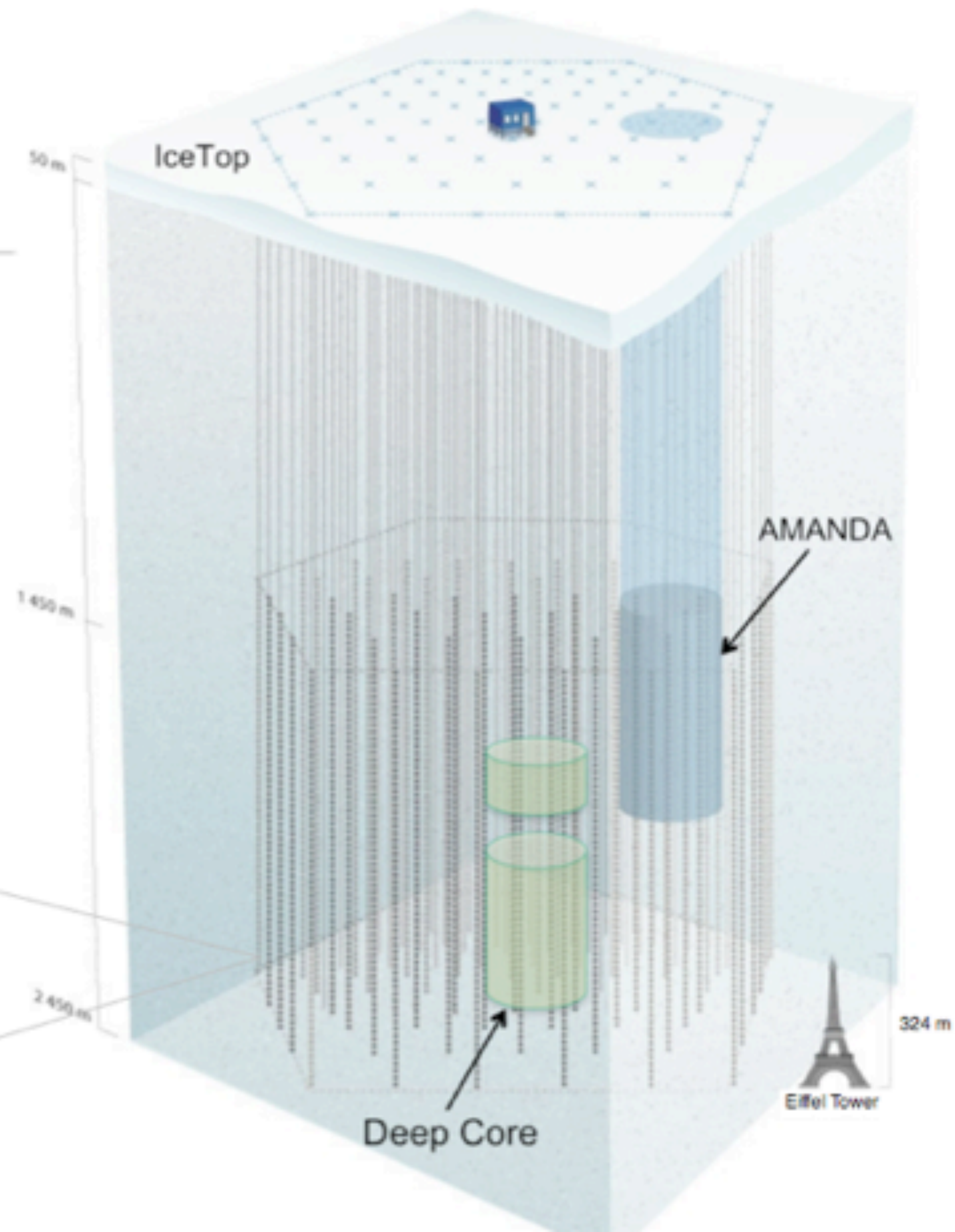
160 tank ice-Cherenkov surface air shower array (IceTop)

Includes DeepCore infill array (sensitivity to lower energies)

All strings now deployed after 7 construction seasons

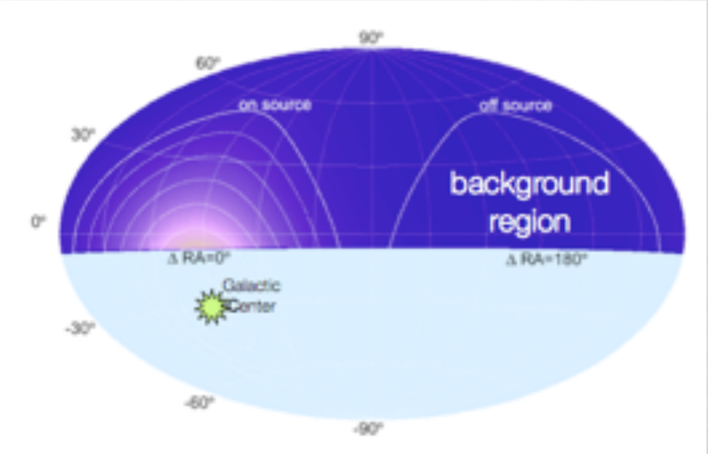


Digital Optical Module (DOM)



IceCube: Galactic Center and Halo

- Search for a signal from the galactic center or halo
- Limits complementary to gamma-rays searches for heavy dark matter



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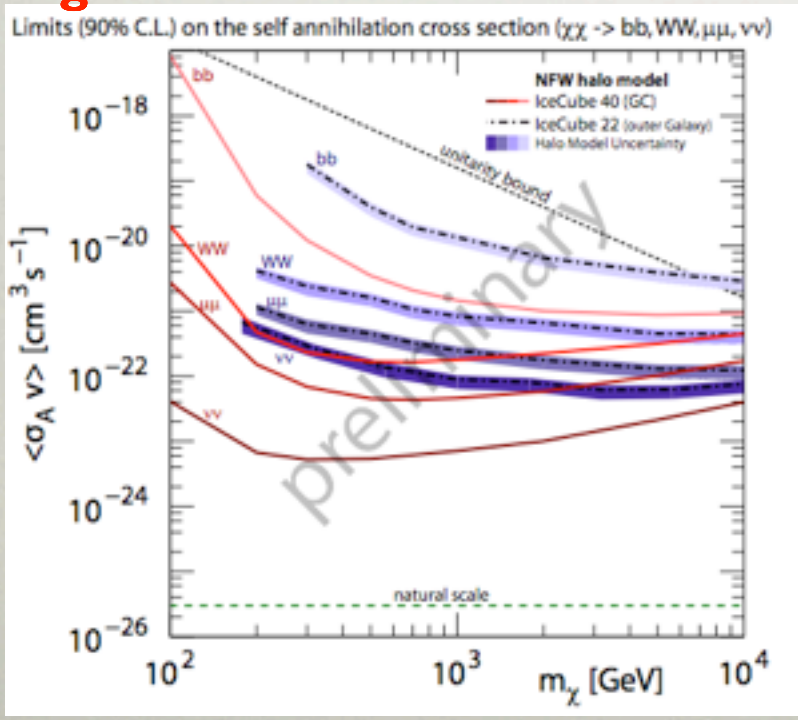
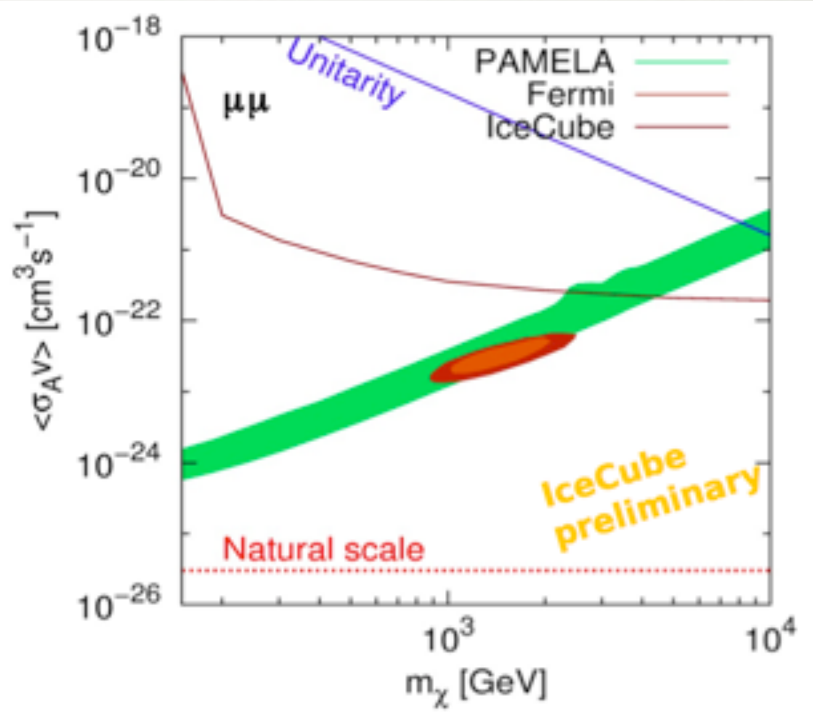
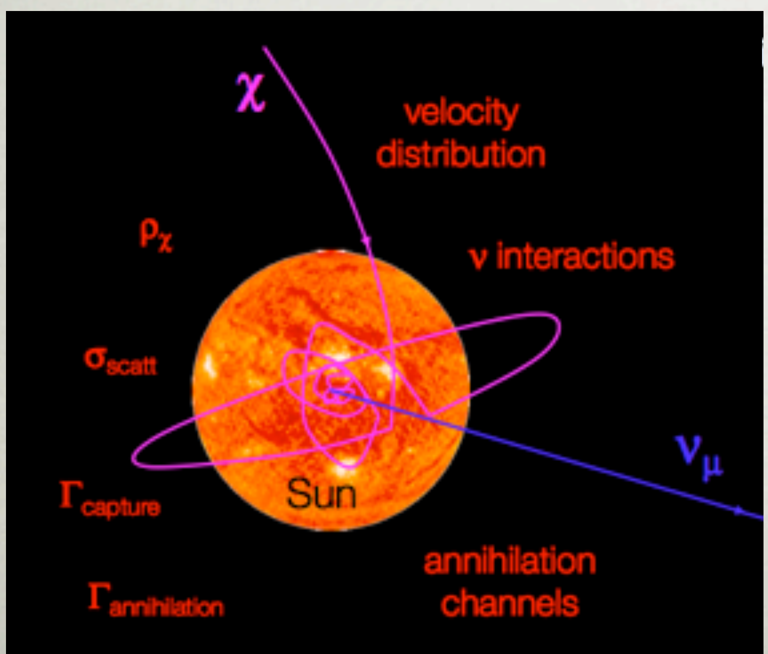
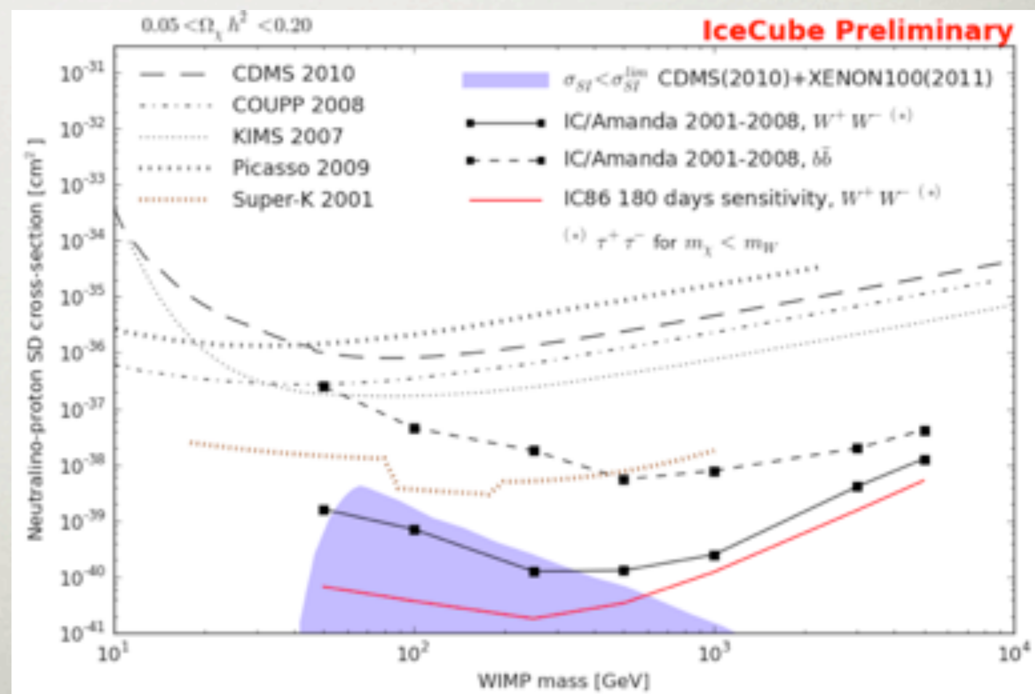




IceCube: Sun

- Dark matter captured in the Sun
- Large model uncertainties (velocity distribution, density, capture rate, scattering cross-section, annihilation cross-section, annihilation channel, energy losses)
- Competitive limits compared to direct detection for spin-dependent interactions for heavy DM





Have We Seen a Signal?

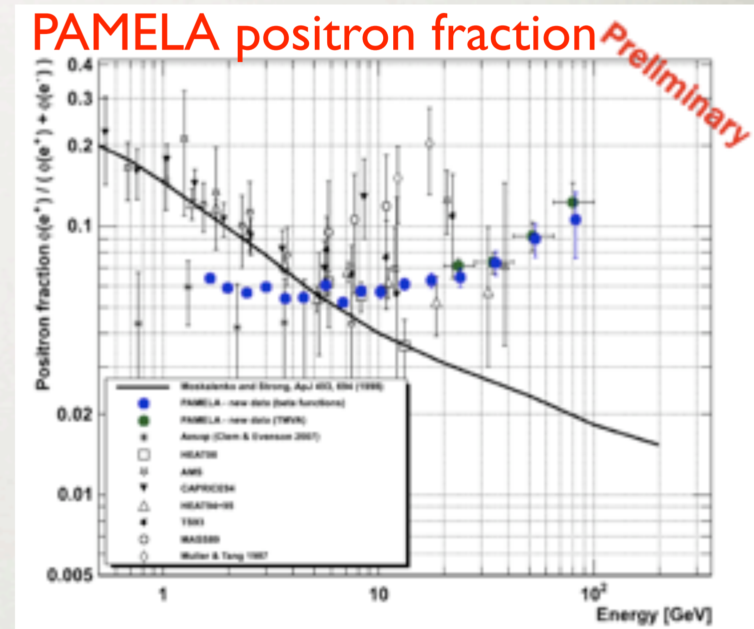
- Recent measurements could be interpreted as a signal of dark matter

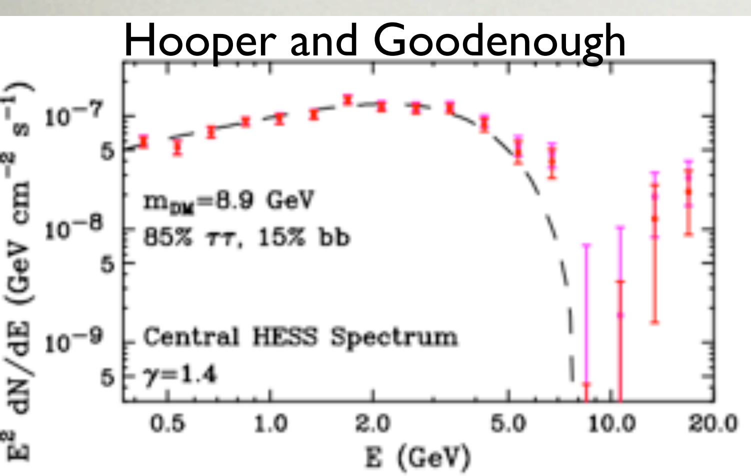
PAMELA positron fraction

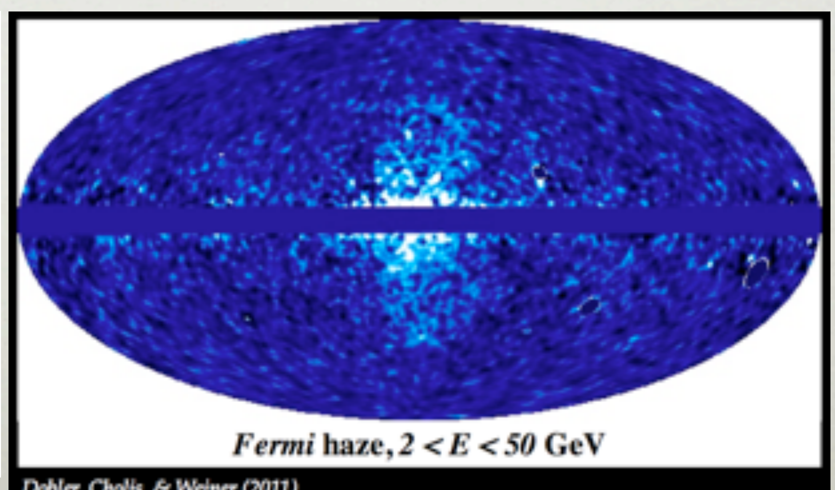
WMAP haze and potentially related excesses in the Fermi data (Finkbeiner et al, Dobler et al)

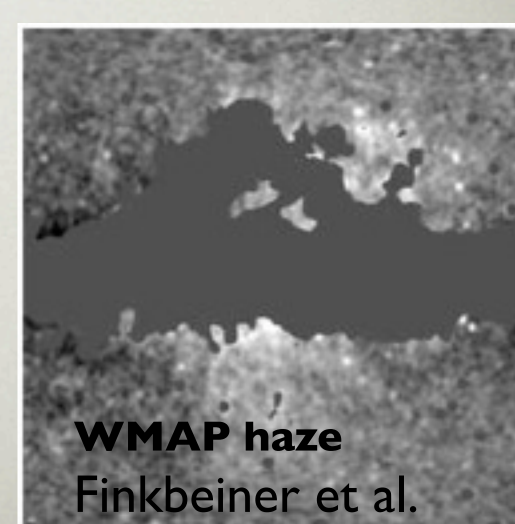
Fermi Galactic center (Hooper and Goodenough)

(...)









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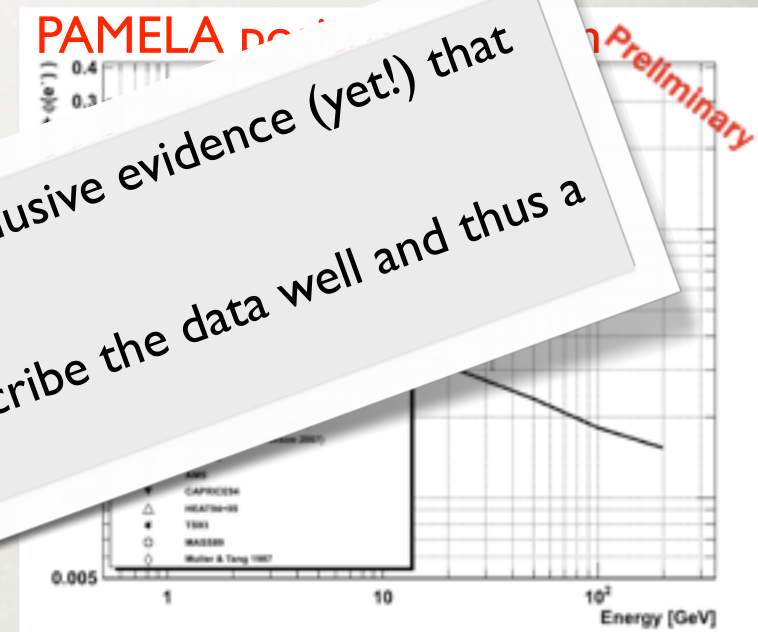
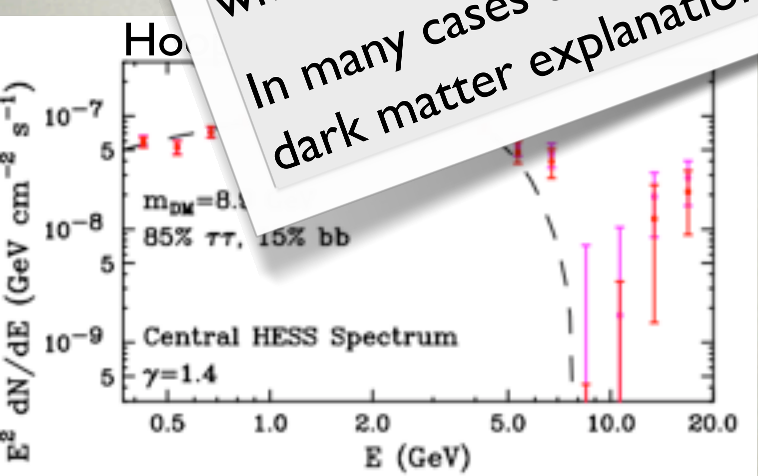
WMAP haze and potentially re
Fermi data (Finkbeiner

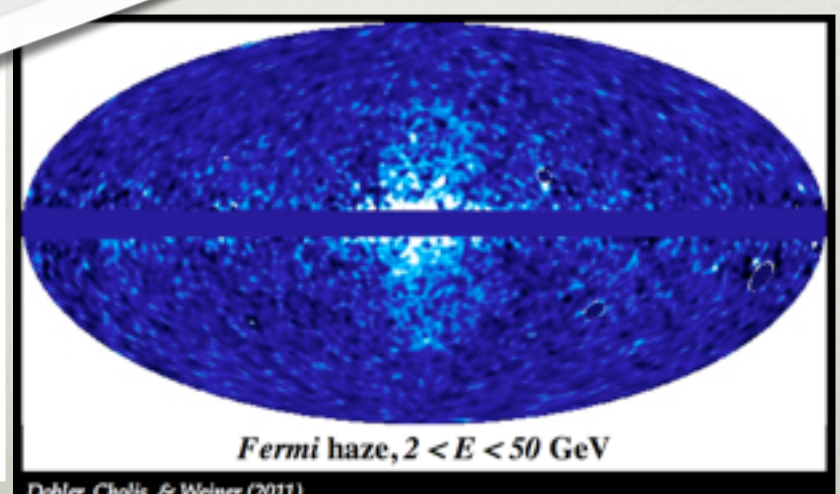
Fermi Galac

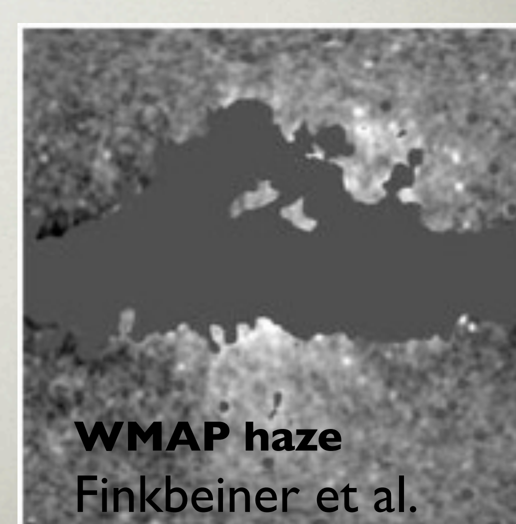
Unfortunately none of these potential signals are conclusive evidence (yet!) that what we are seeing is dark matter

In many cases other more prosaic explanations describe the data well and thus a dark matter explanation is controversial









Conclusions

- No discovery yet... however promising constraints on the nature of DM have been placed.
- Looking forward:
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  - Some analyses will further benefit from multi-wavelength observations (e.g. dSph, GC.) And if a signal is observed elsewhere (e.g. LHC) it's likely to make our job easier!
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Conclusions

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Thank you!